Skew Effects On Steel Highway Bridges

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HDR

Presentation Outline

- Introduction
- Behavior of Skewed Structures
- Cross Frames and Diaphragms
- Framing Plan
- Analysis
- Case Study
  - Detailing and Fit
  - Deck Placement Considerations
  - Impacts to Pier Design
  - Effects on Bearing Design
  - Expansion Joints
  - Conceptual Erection Sequence
  - Shop Fit-Up
- Summary

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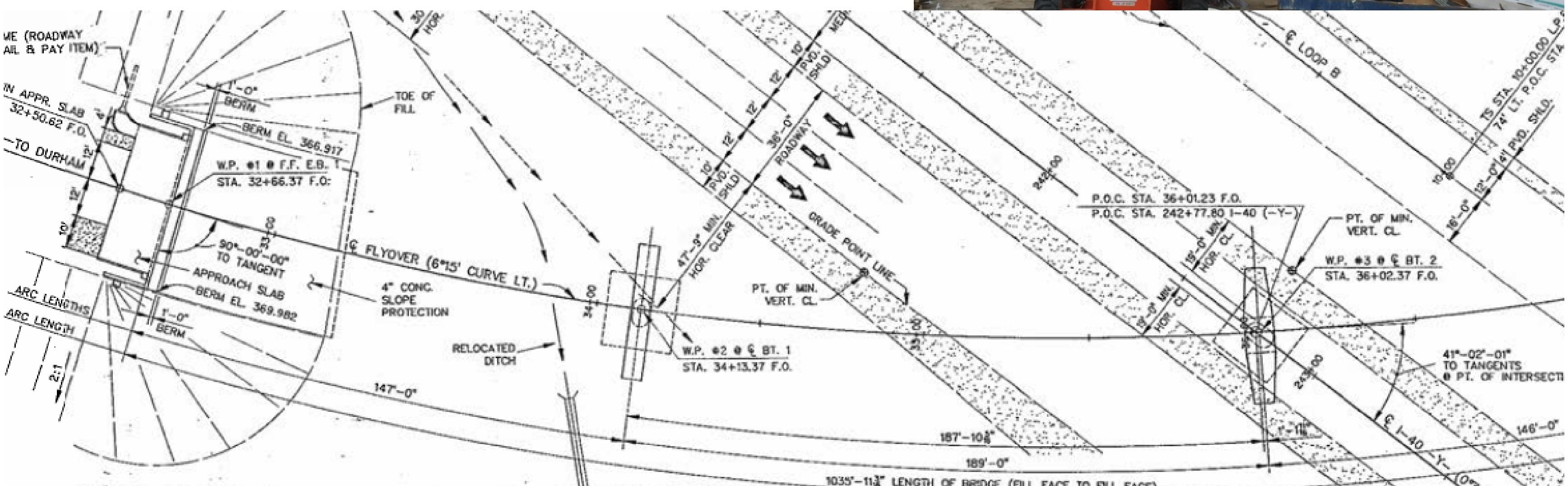
Introduction

- Skew can complicate design, detailing, fabrication, and construction of bridges
- Skew can lead to construction delays and claims if not appropriately accounted for
- Skewed bridges are becoming more prevalent especially in tight urban areas
- We need a plan to address the issues with skew

Introduction

First step is in the planning process try to minimize skew if possible

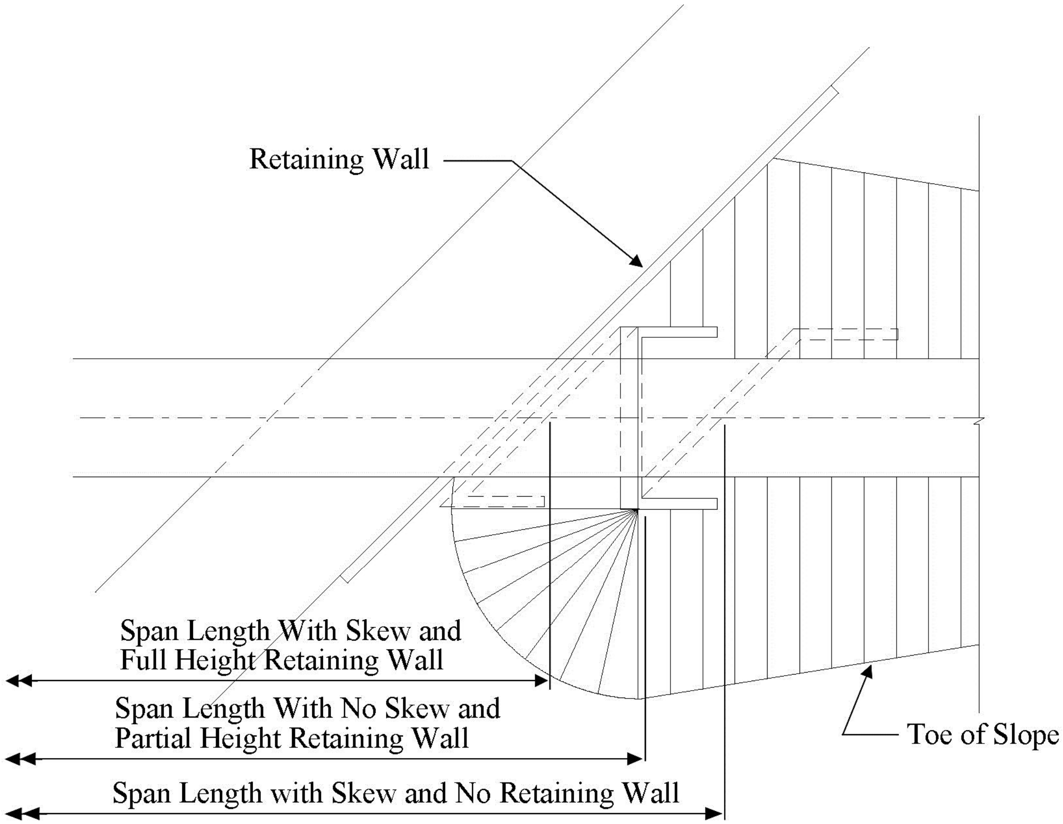
- Work with roadway designers to adjust the alignment
- Consider lengthening bridge
- Consider integral pier



Introduction

First step is in the planning process try to minimize skew if possible

- Consider retaining wall to allow the use of a non-skewed abutment



Introduction

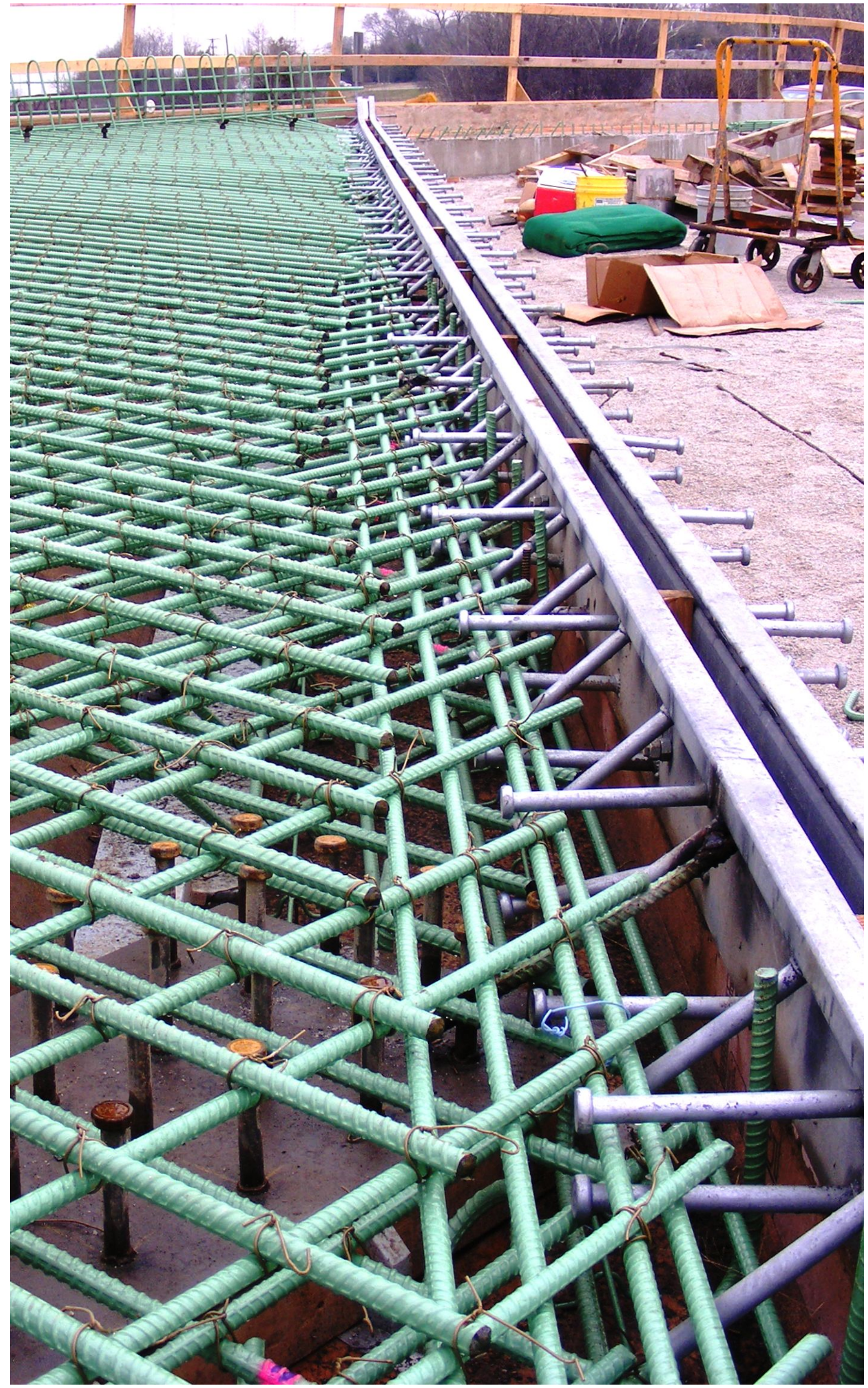
Recognize skew challenges:

- Introduce torsion in the girders
- Large cross frame forces
- Different thermal movements
- Additional detailing considerations
- Longer substructure elements

Introduction

Next steps to address skew:

- Understand the behavior of skewed structures
- Determine appropriate level of analysis
- Develop optimal framing plan
- Detail skewed bridges properly to mitigate skew effects



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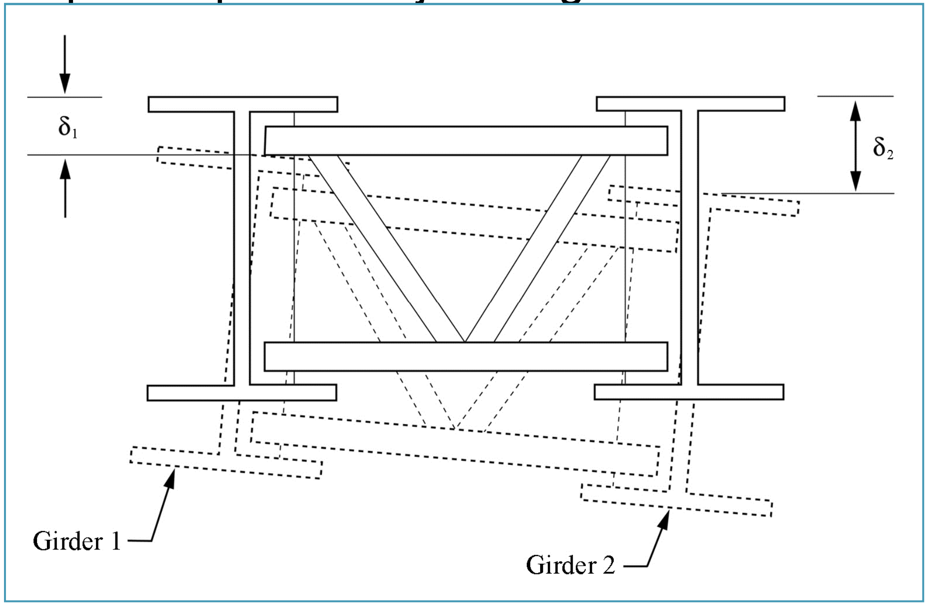
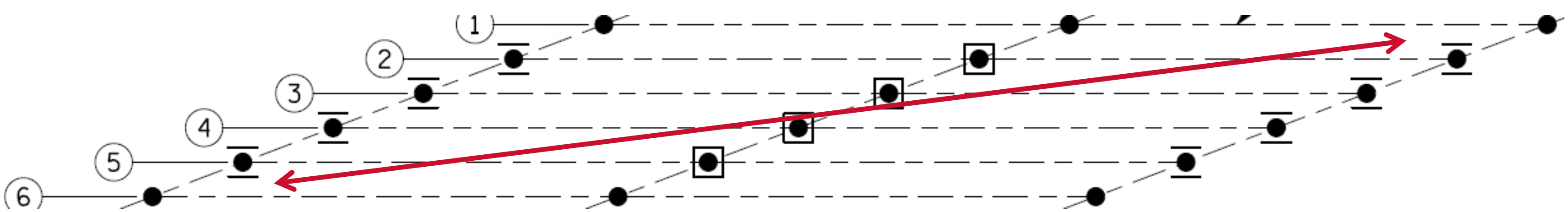
Behavior of Skewed Structures

- Girder differential vertical deflection causes lateral deflections and twist
- Due to the skew and associated framing, skewed girders will deflect vertically, and rotate transversely during deflection
- Shifting of load between girders creates torsion and changes the vertical and horizontal reactions
- Cross-frames attempt to equalize adjacent girder deflections



Behavior of Skewed Structures

- Elastomeric bearings performance

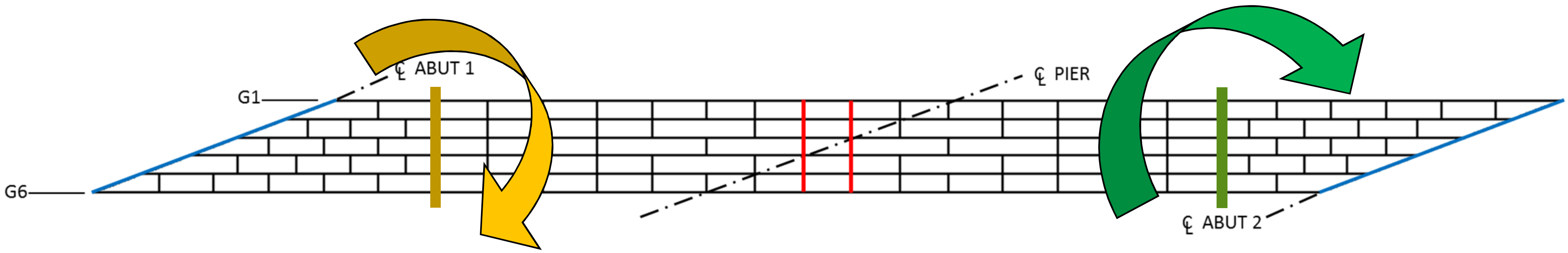


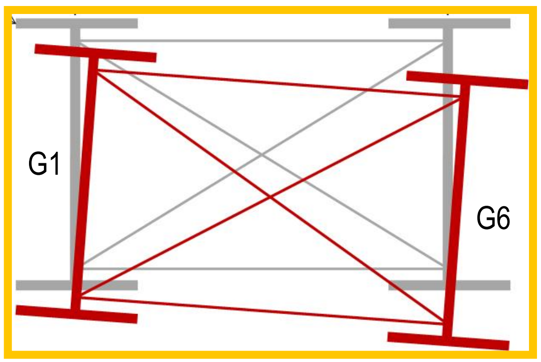
Behavior of Skewed Structures

- Example 1

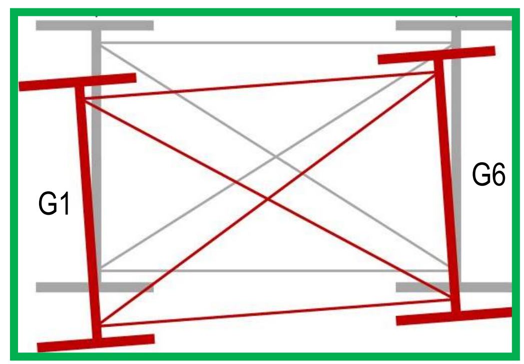
Behavior of Skewed Structures

- Opposite direction of rotation between span 1 and 2

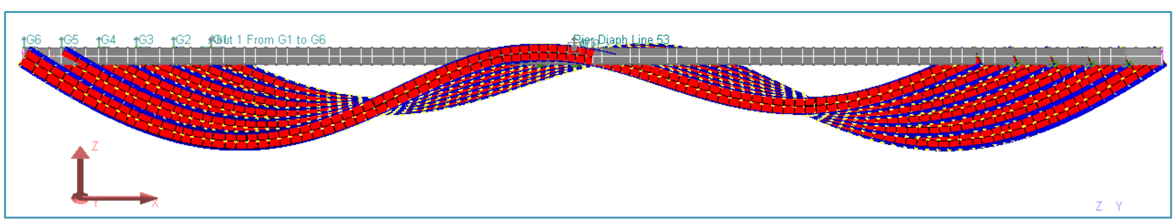




SPAN 1 – LOOKING TOWARDS ABUT 2

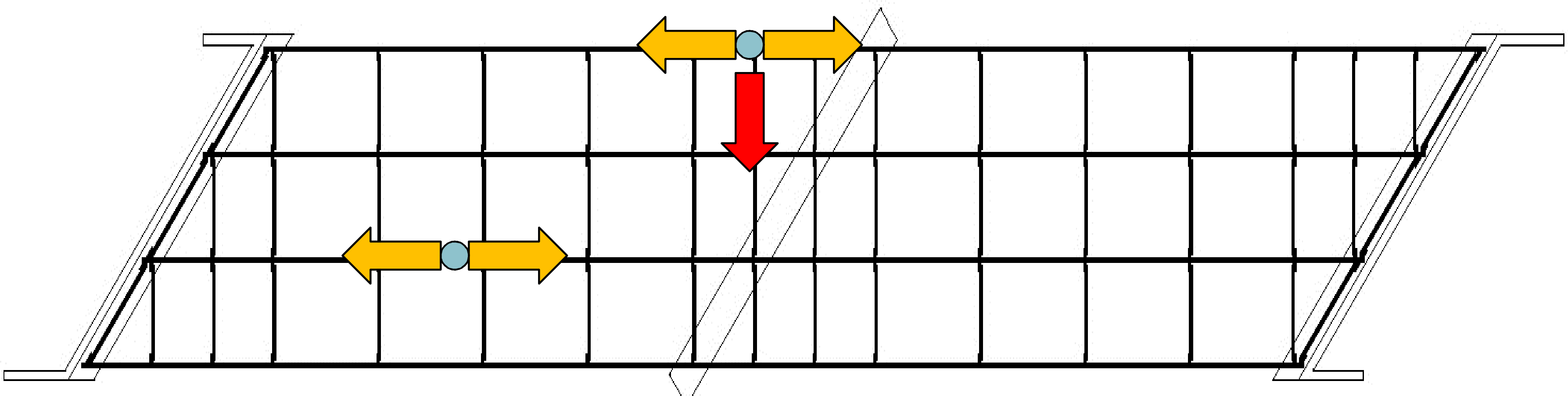


SPAN 2 – LOOKING TOWARDS ABUT 2



Behavior of Skewed Structures

- Transverse load paths through cross frames
- "Nuisance Stiffness" Effects
- Lateral reactions develop at the bearings

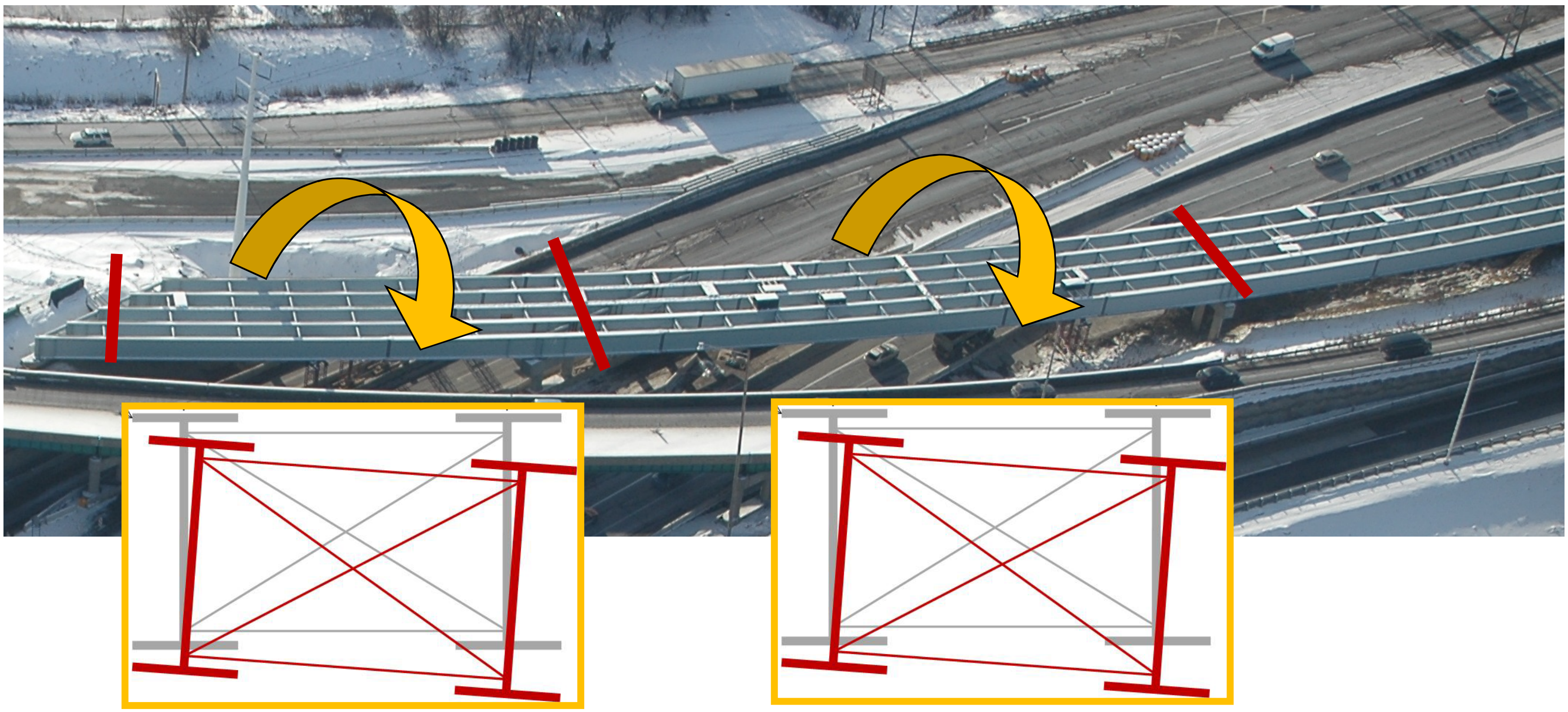


Behavior of Skewed Structures

- Example 2

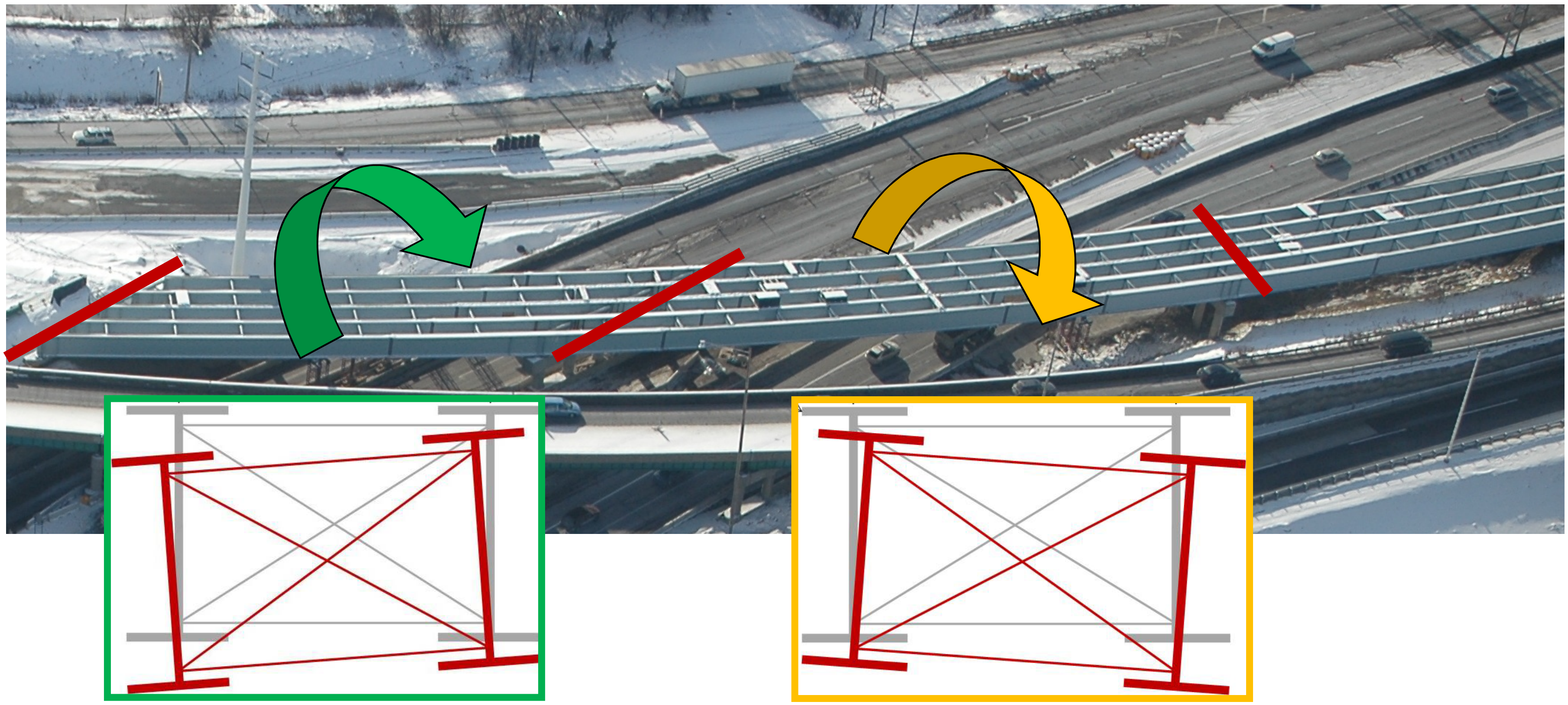
Behavior of Skewed Structures

- Effects of Curvature (Radial Piers)



Behavior of Skewed Structures

- Effects of Curvature and Skewed Piers
- Skewed pier leads to longer center span for outside girder



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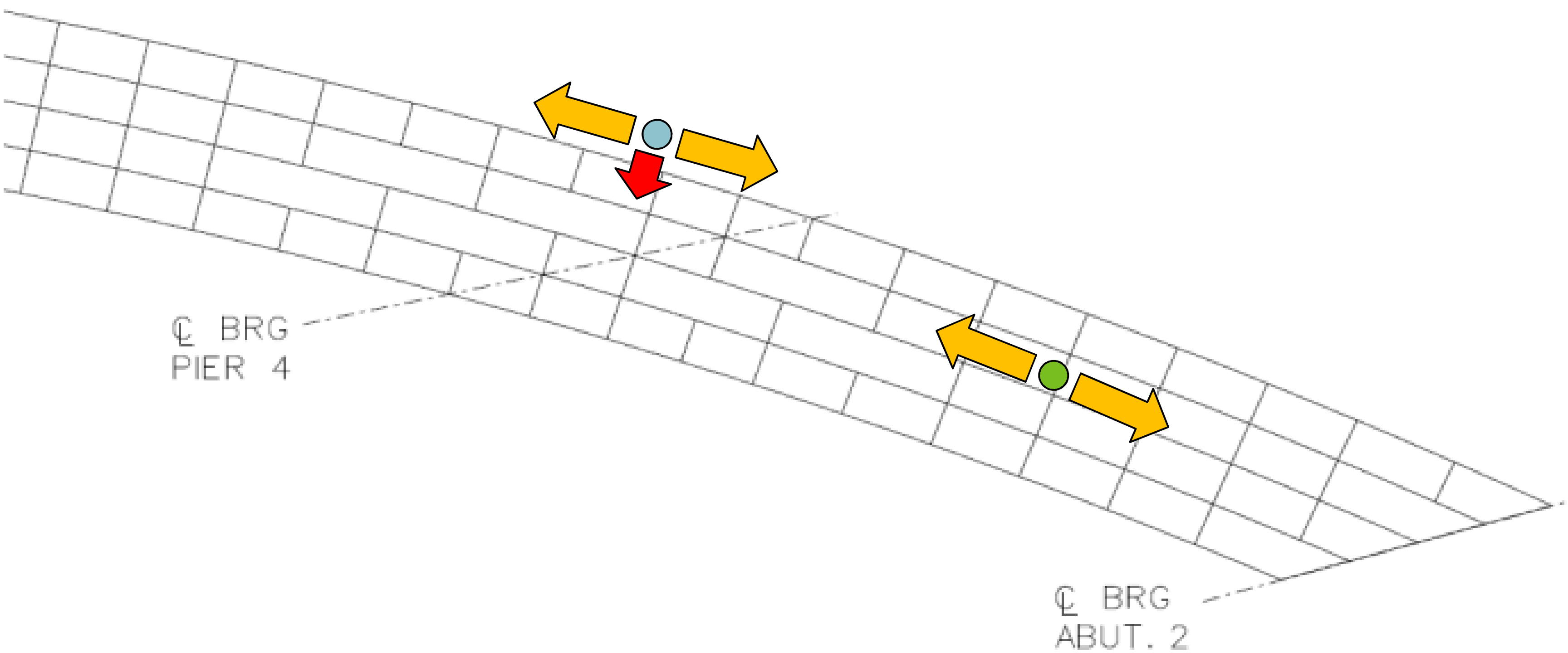

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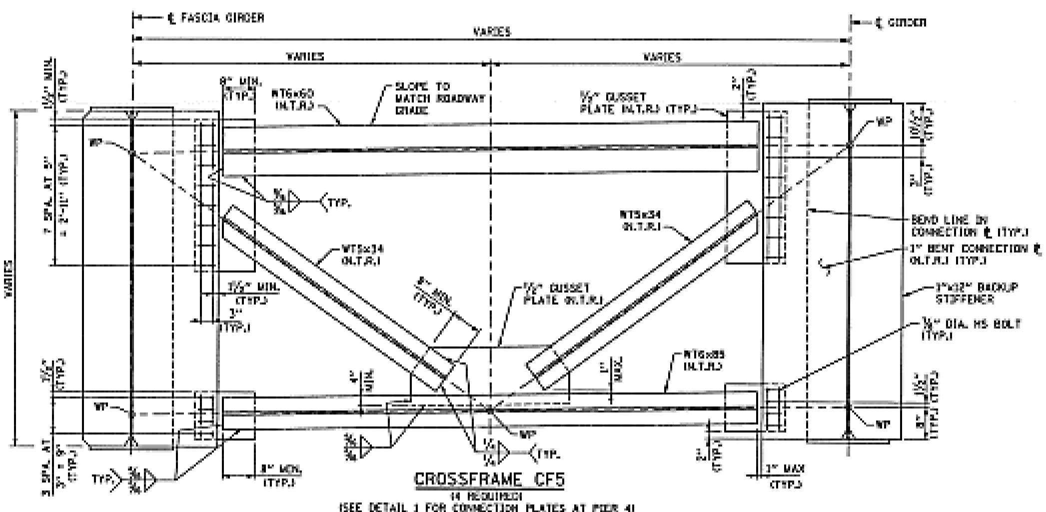
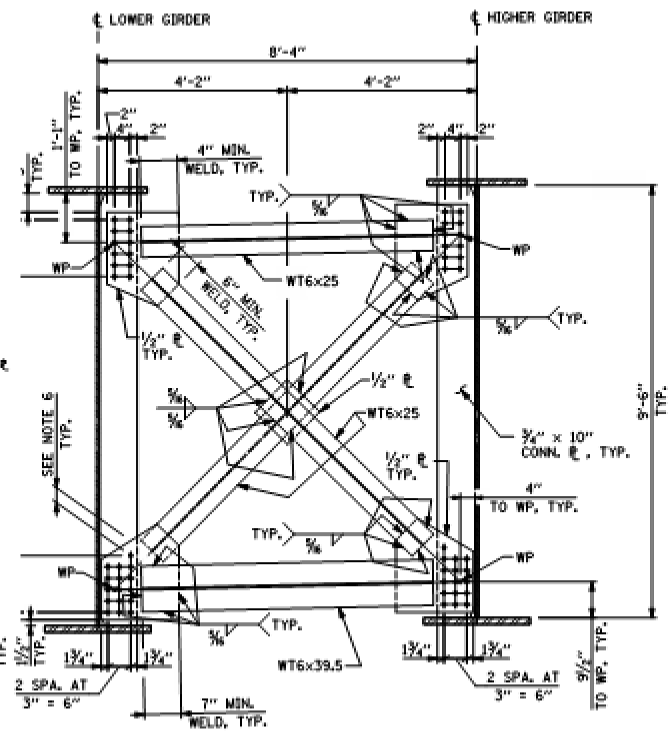
Cross Frames and Diaphragms of Skewed Structures

- Straight bridges diaphragms brace compression flanges and transfer wind loads
- For skewed and curved bridges the diaphragms and cross frames members may carry significant load through transverse load paths
- K-type and X-type are utilized based on girder spacing and depth
- Cross frame stiffness is greater than the girder torsional stiffness so the cross frame remains rigid while the girders twist.





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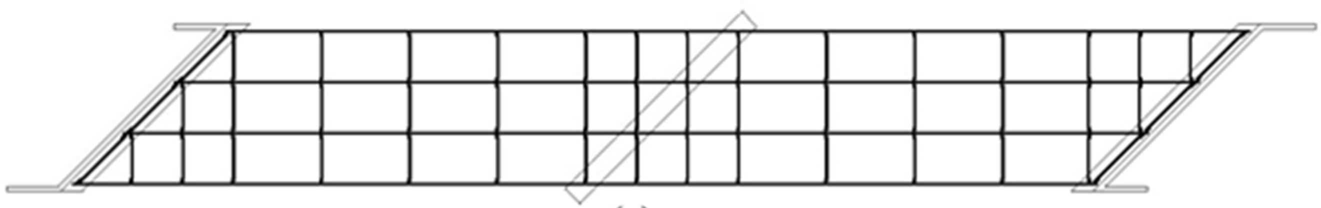
Framing Plan

- The effects of skew on steel I-girder bridges depend on the severity of skew and type of framing
- Integrated system behavior is recognized with framing plan arrangement
- Continuous versus staggered diaphragms
  - o Manage Uplift
  - o Flange Lateral Bending



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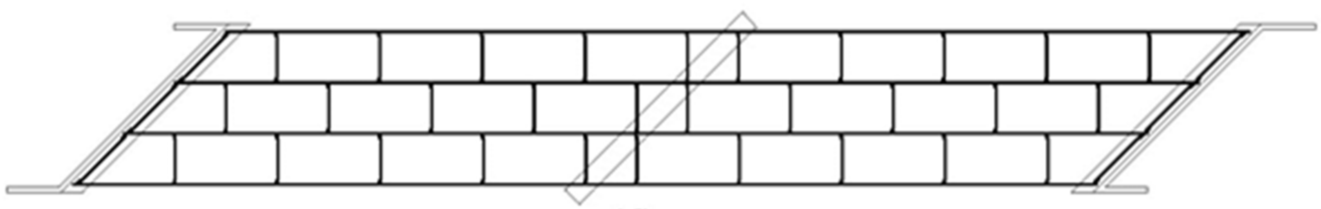

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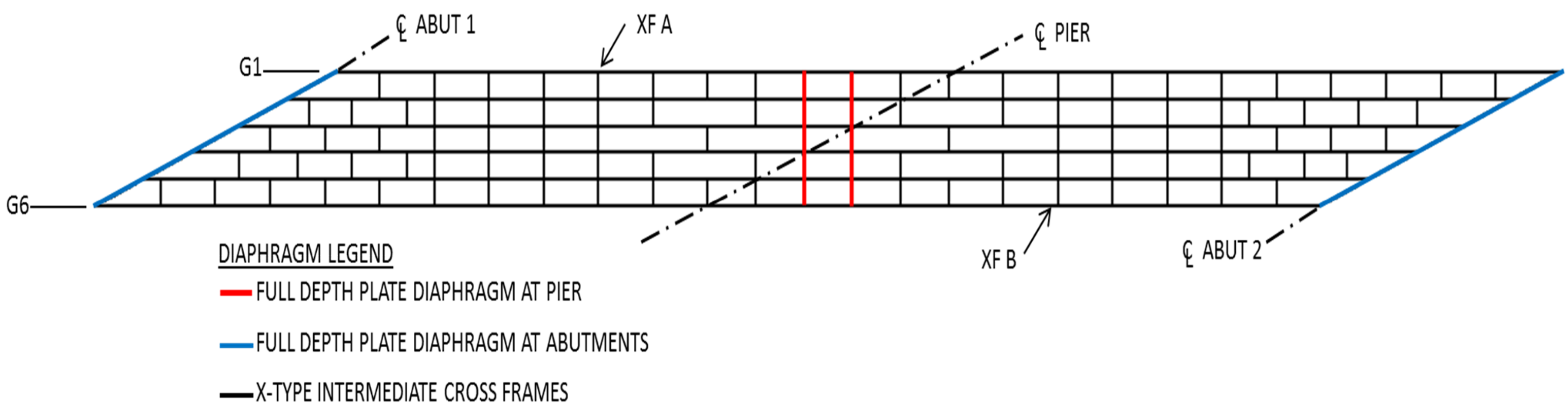
Framing Plan - Example 1

- Selectively remove cross-frames near the pier
  - Nuisance stiffness, reduce transverse load paths
- Use full-depth diaphragms at interior pier location
  - Attract load at two distinct locations
- Use staggered cross-frame pattern at skewed ends
  - Eliminate the transverse load paths

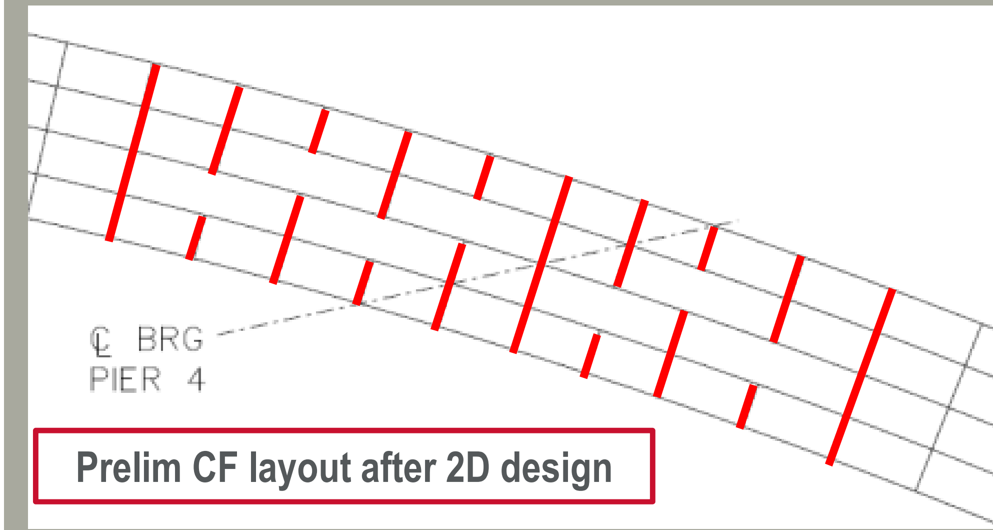


Framing Plan - Example 1

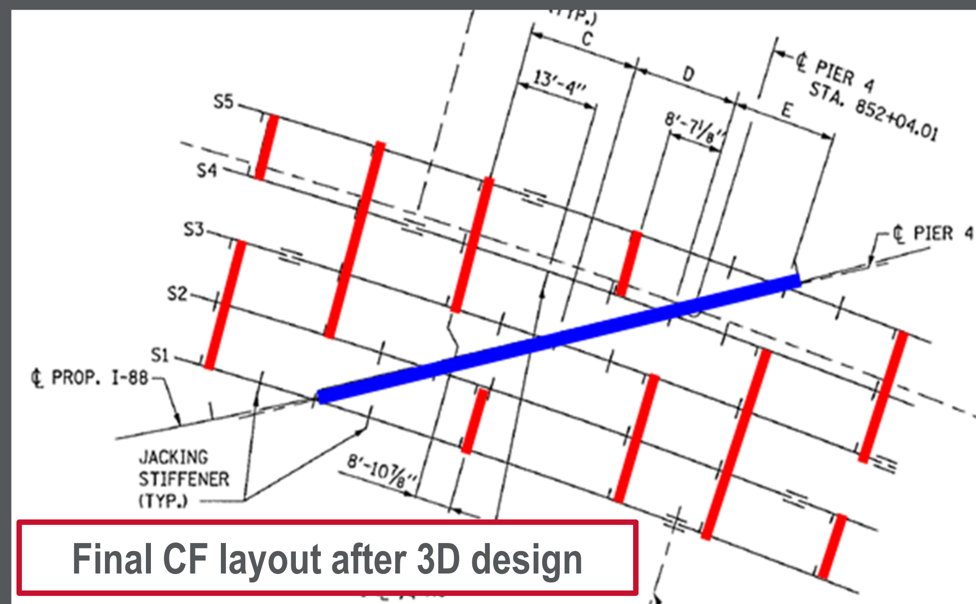
- Difference in cross frame member sizes, near skewed pier and typical intermediate

Framing Plan - Example 2

- Based on initial 3D analysis, rearrange cross frames at skewed pier 4
  - Use 3D model to investigate layouts
  - Reduce “nuisance stiffness”
  - Place cross frames along skew
  - No radial frames at skewed pier
  - Omit certain cross frames beyond pier
  - Relieve transverse stiffness & reduce cross frame forces



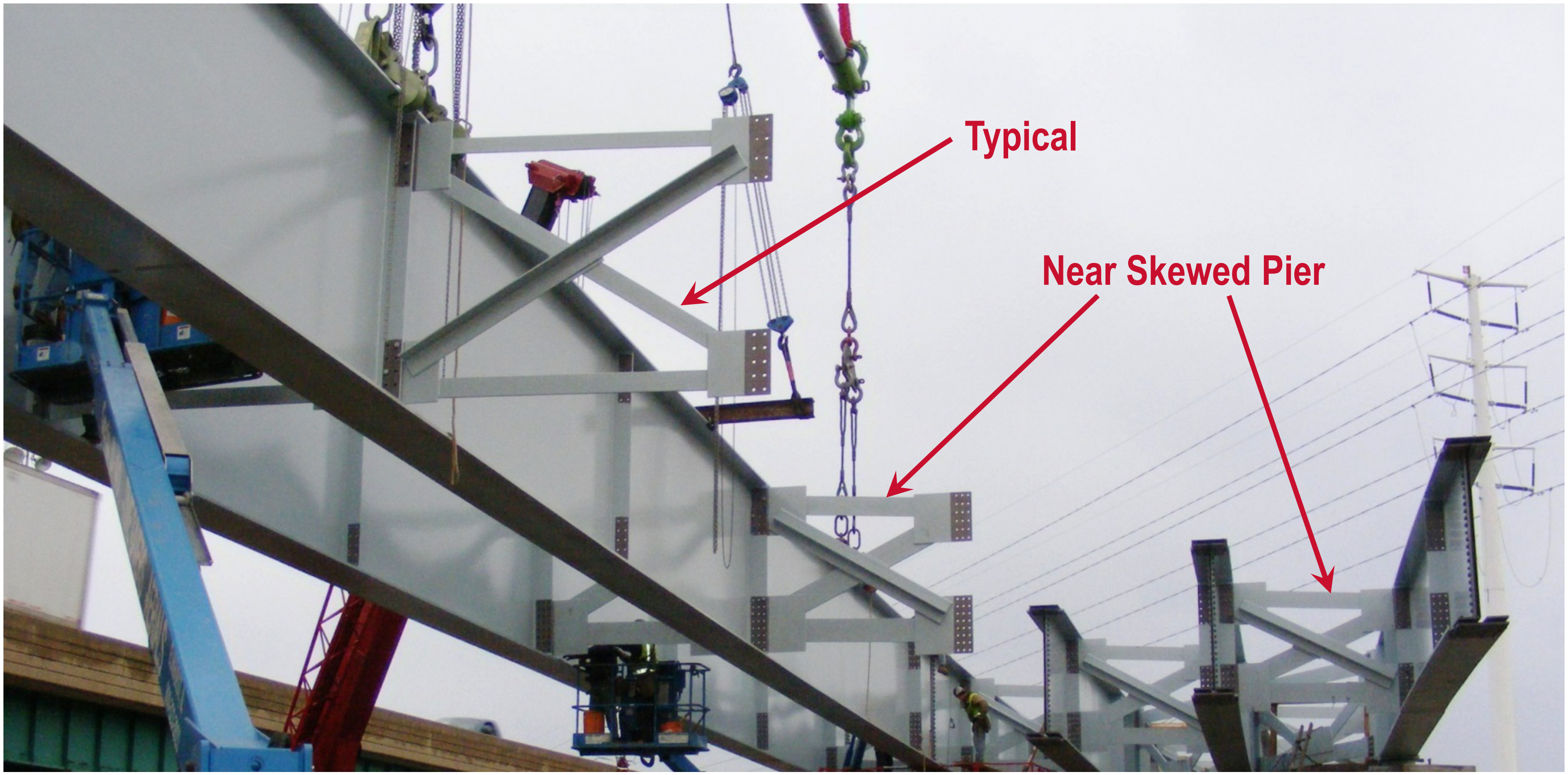
Prelim CF layout after 2D design



Final CF layout after 3D design

Framing Plan - Example 2

- Difference in member sizes, near skewed pier and typical intermediate



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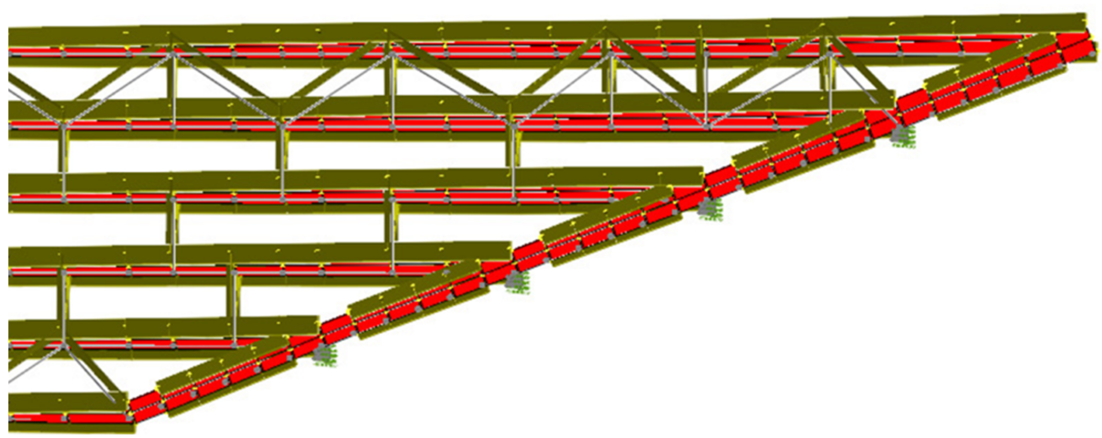
Appropriate Analysis

- Level of analysis is based on the configuration of the bridge
  - NCHRP Report 725 introduced a scoring method to assess the accuracy of the analysis method.
  - Based on a skew index that considers the width of the bridge, the skew angle, and the span length
- Various responses considered
  - Major-axis bending
  - Vertical displacements
  - Cross frame forces
  - Flange lateral bending
  - Girder layover at bearings



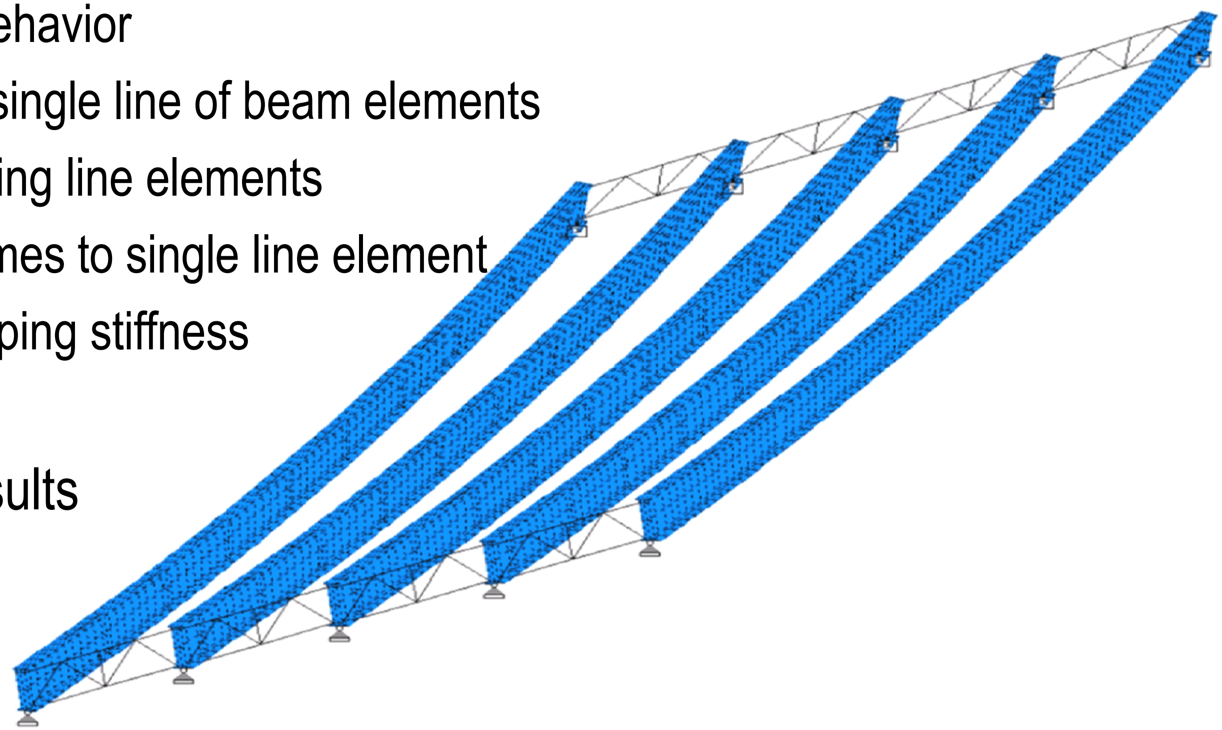
Appropriate Analysis

- 1D Line Girder Analysis
  - Isolates and analyzes a single girder
  - Loads are distributed to each girder by way of distribution factors
  - Adequate for fairly simple structures with little to no skew angle

Appropriate Analysis

- 2D grid analysis:
  - Begins to address system behavior
  - Girders are modeled with a single line of beam elements
  - Deck is modeled in strips using line elements
  - Limits modeling of cross frames to single line element
  - Generally cannot model warping stiffness

- May produce inaccurate results
  - Cross-frame forces
  - Bearing Reactions
  - Girder displacements



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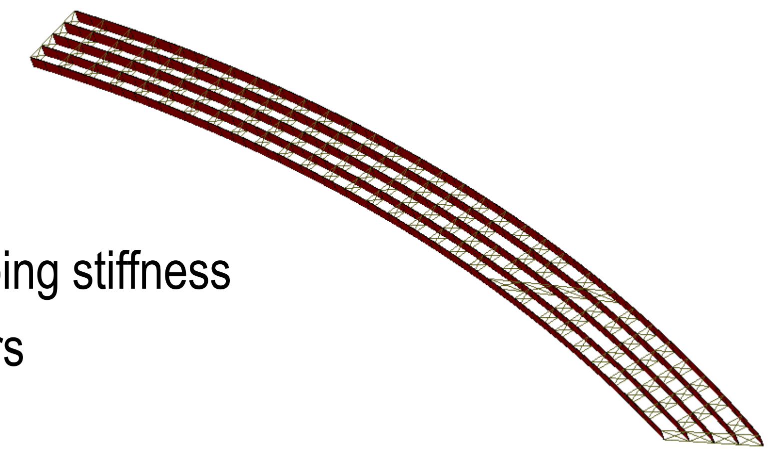
Appropriate Analysis

- 2D grid analysis shortcoming:
  - 2D software only considers St. Venant (pure) torsional stiffness of the girders while neglecting warping torsional stiffness component. Warping torsion produces shear stress and normal stresses in which cross-sections do not remain plane.
  - Significant since I-girders as open, thin-walled sections, primarily carry torsion by warping
  - The lack of torsional stiffness in the I-girder leads to an inability to accept significant load transferred from the cross frames. As a result the 2D model underestimates transverse load paths and cross frame forces in the skewed bridge framing.

Appropriate Analysis

- 3D Finite Element Analysis
  - Girder flanges are modeled with beam elements and webs are modeled using plate or shell elements
  - Explicitly model all cross-frame members using truss elements for K and X type cross frames and plate or shell elements for the webs of full the depth diaphragms with beam elements for the diaphragm flanges.
  - The deck is typically modeled using brick-type elements or shell elements.



- Benefits
  - Accurate cross-frame forces
  - Properly model girder torsional stiffness and warping stiffness
  - Properly accounts for load shifting between girders
  - Properly capture horizontal and vertical reactions

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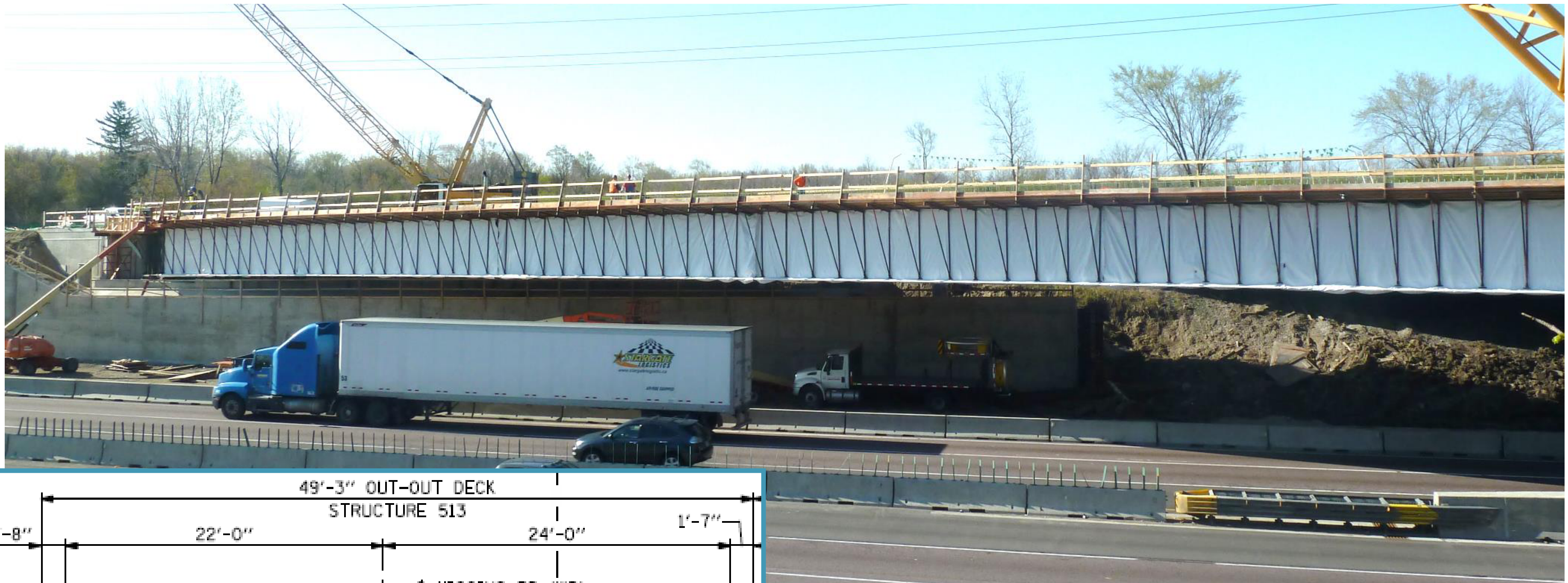
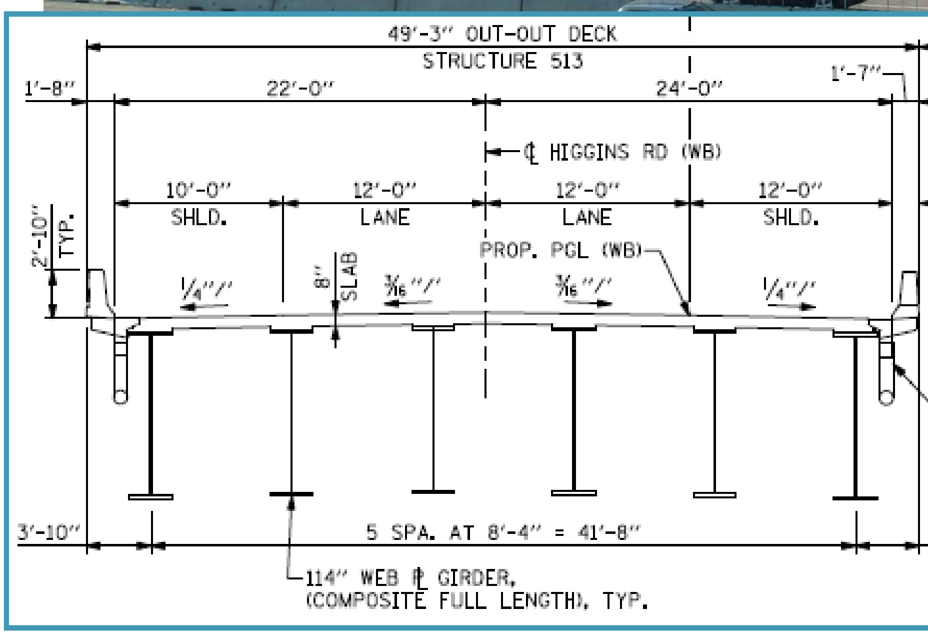
Case Study Overview

Exist. WB Bridge:
- 5 simple spans: 471 ft total length
- 60” deep plate girders
- WB fracture critical substructure
- WB no skew counterfort wall abut

Exist. EB Bridge
- 3 continuous spans: 503 ft total length
- 81” deep plate girders
- skewed counterfort wall abut

Case Study Overview

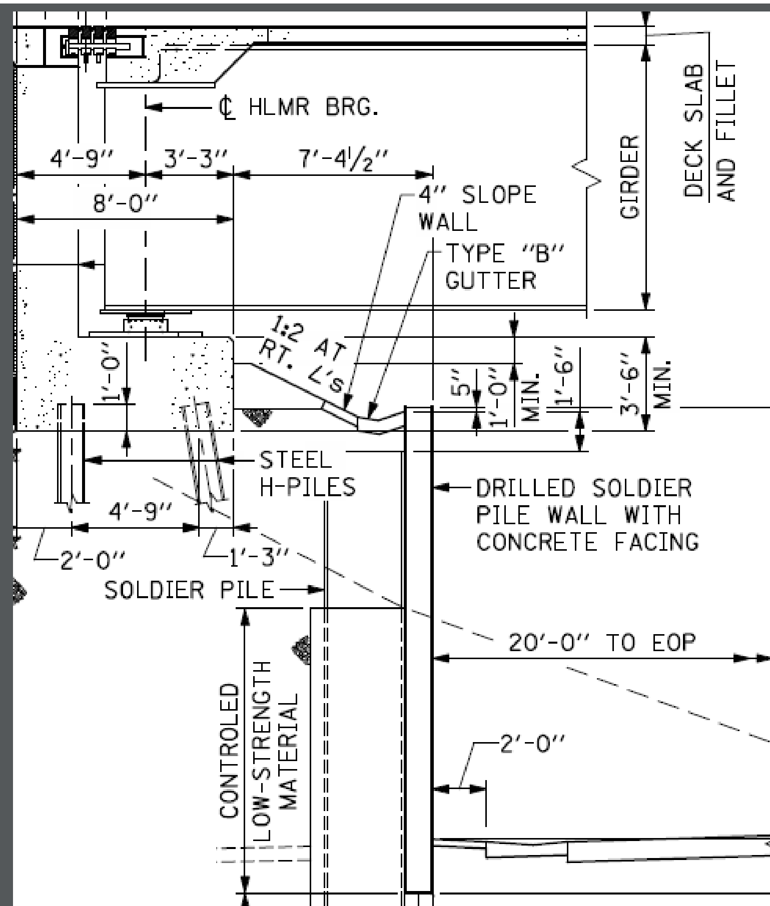




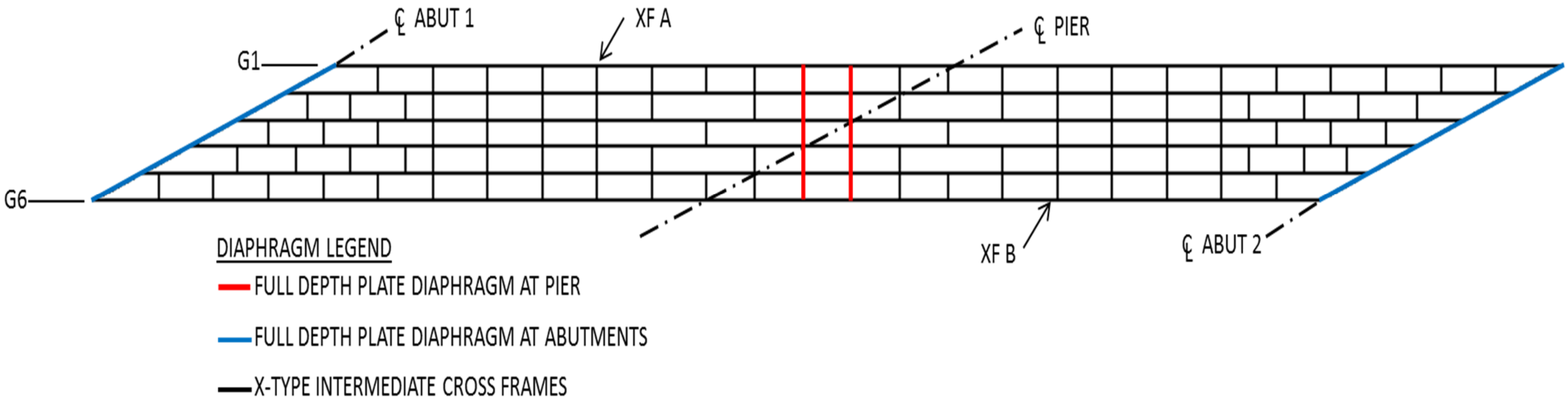
- 70-degree skew
- Two spans @ 280 ft = 560 ft total length
- Deck width: 49'-3" with three lanes
- 6 plate girders
- Webs: 13/16" x 9'-6"
- Flanges: 1.5"x26" to 3"x34"
- X-type intermediate cross-frames
- Full-depth abutment diaphragm along skew
- Full-depth pier diaphragm normal to girders

Case Study Overview

- Stub abutments behind 600 ft long soldier pile walls
- Modular swivel type expansion joints at each abutment
- Multi-column pier supported on 4 rows of battered piles

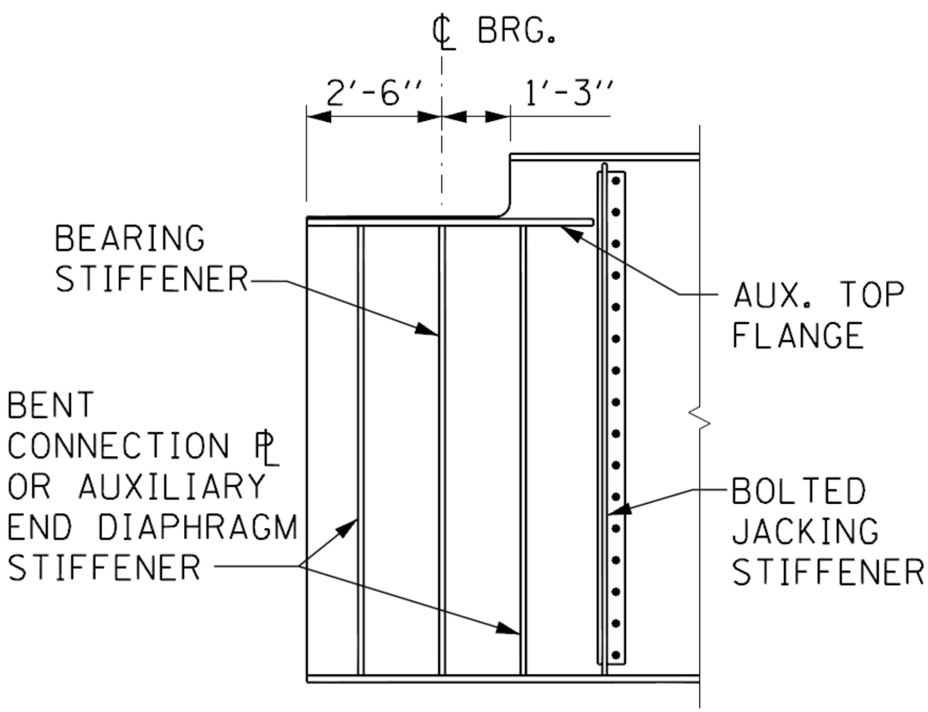


Case Study Overview



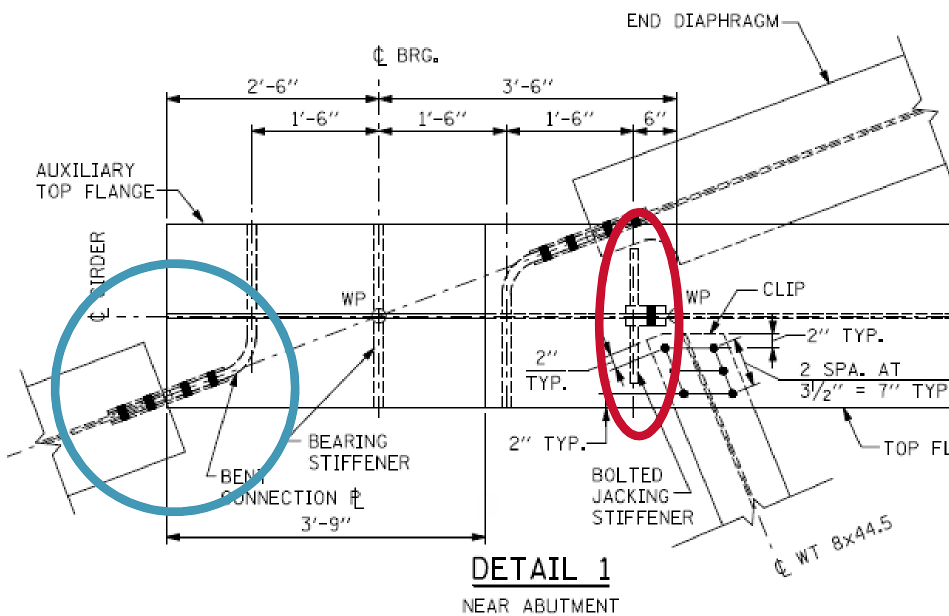
Detailing – End Diaphragm

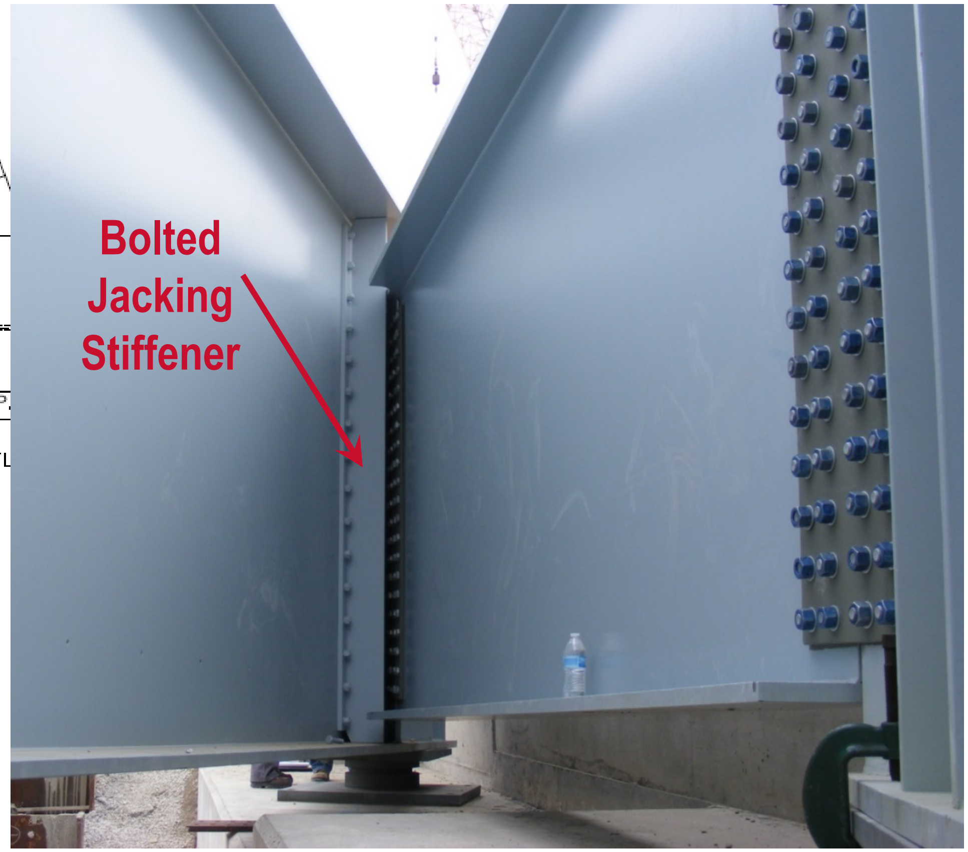
- Full-depth end diaphragm (length ~ 23.5 ft)
  - Too long for a K-type cross-frame
- Auxiliary stiffeners (back-up stiffeners)



Detailing – End Diaphragm

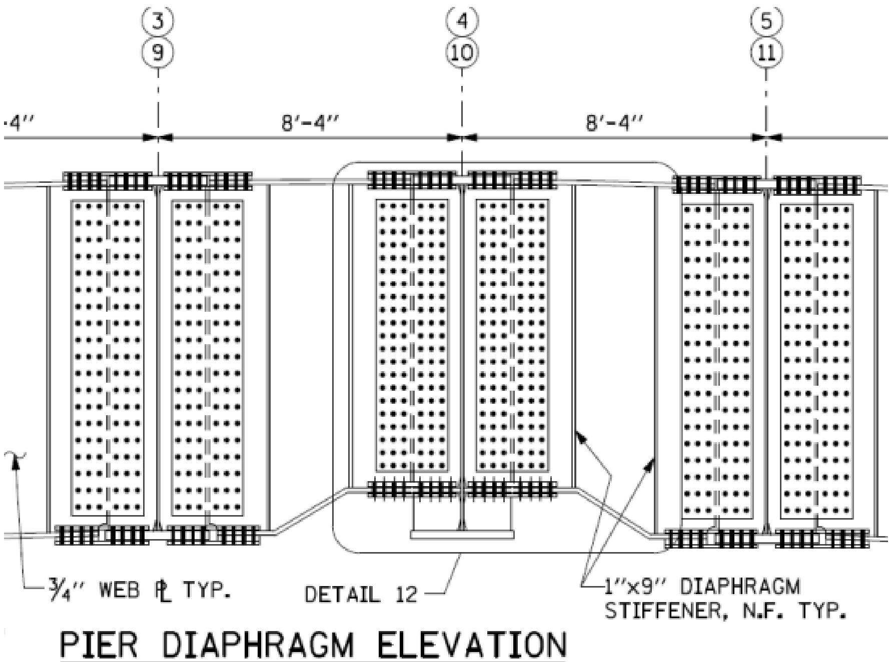
- Full-depth diaphragm connected to bent stiffener plate
- Bolted jacking stiffener installed after end diaphragm due to conflict





Detailing – Pier Diaphragm

- Detail to avoid interference with fixed bearing at skewed pier



Fit Condition

- Severe skew leads to:
  - Out-of-plumb webs after dead load is applied
  - Excessive bearing rotation
  - Try to control this rotation via detailing
- AASHTO Article 6.7.2
  - Fit condition to be specified in the plans
- 3 choices:
  - No load fit (NLF)
  - Steel dead load fit (SDLF)
  - Total dead load fit (TDLF)

Fit Condition

Cross-frames connect to girder locations that have different dead load deflections (differential).

For SDLF and TDLF the cross-frames are forced into place and the girders are twisted out of plumb during the erection.

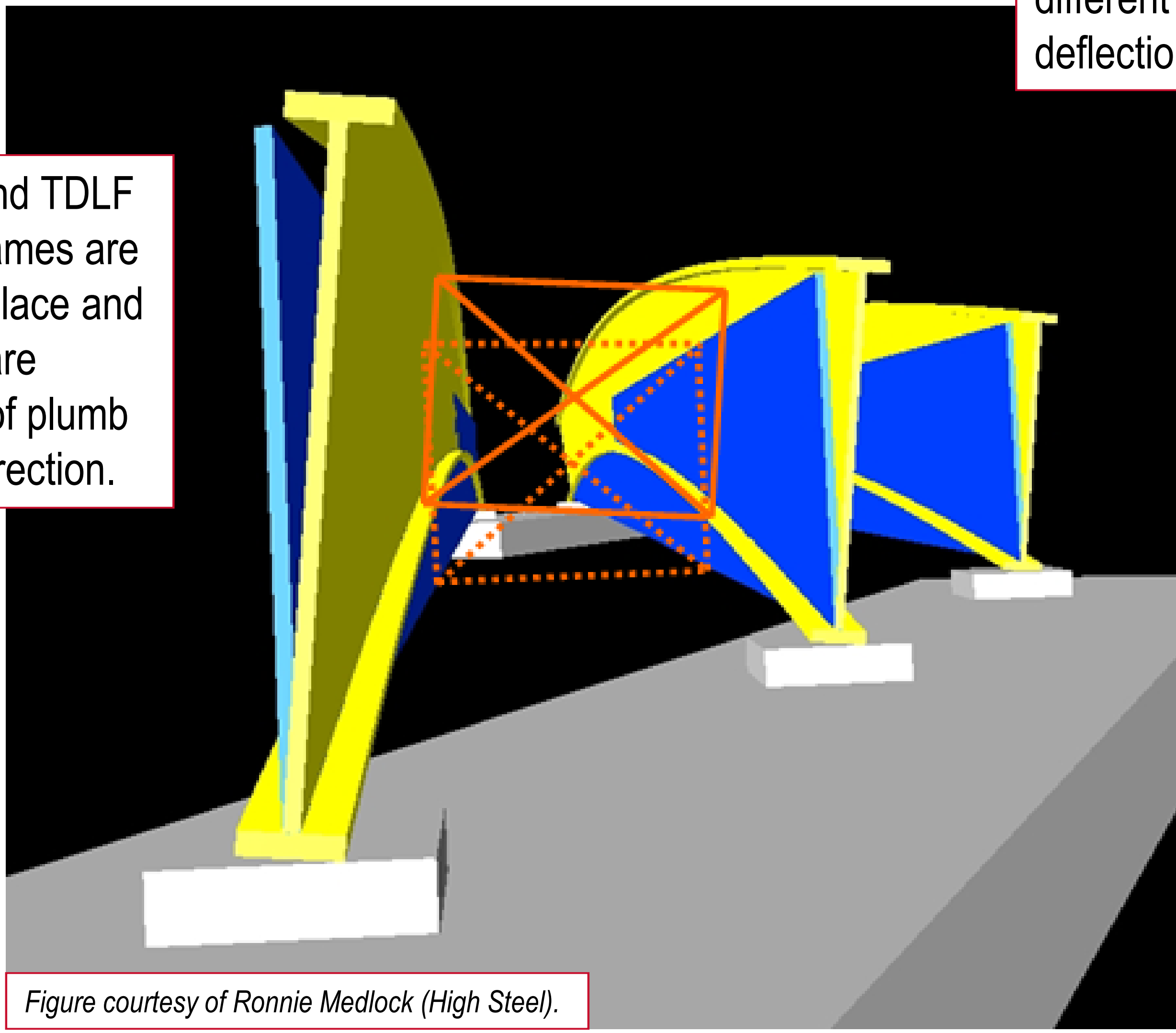


Figure courtesy of Ronnie Medlock (High Steel).

Fit Condition

- Steel Dead Load Fit (SDLF) chosen
  - o Disc bearing can accommodate rotations
    - Concrete dead load
    - Live load
  - o Erection simpler & faster than TDLF
  - o Limited construction windows

https://www.aisc.org/globalassets/nsba/technical-documents/skewed-curved-steel-bridges-august-2016-summary-final.pdf

Skewed and Curved
Steel I-Girder Bridge Fit

NSBA Technical Committee, Fit Task Force
Brandon Chavel, Domenic Coletti, Karl Frank, Mike Grubb, Bill McEleney, Ronnie Medlock and Don White

This is a stand-alone summary that is complimentary to a larger guide document on fit published by the NSBA.

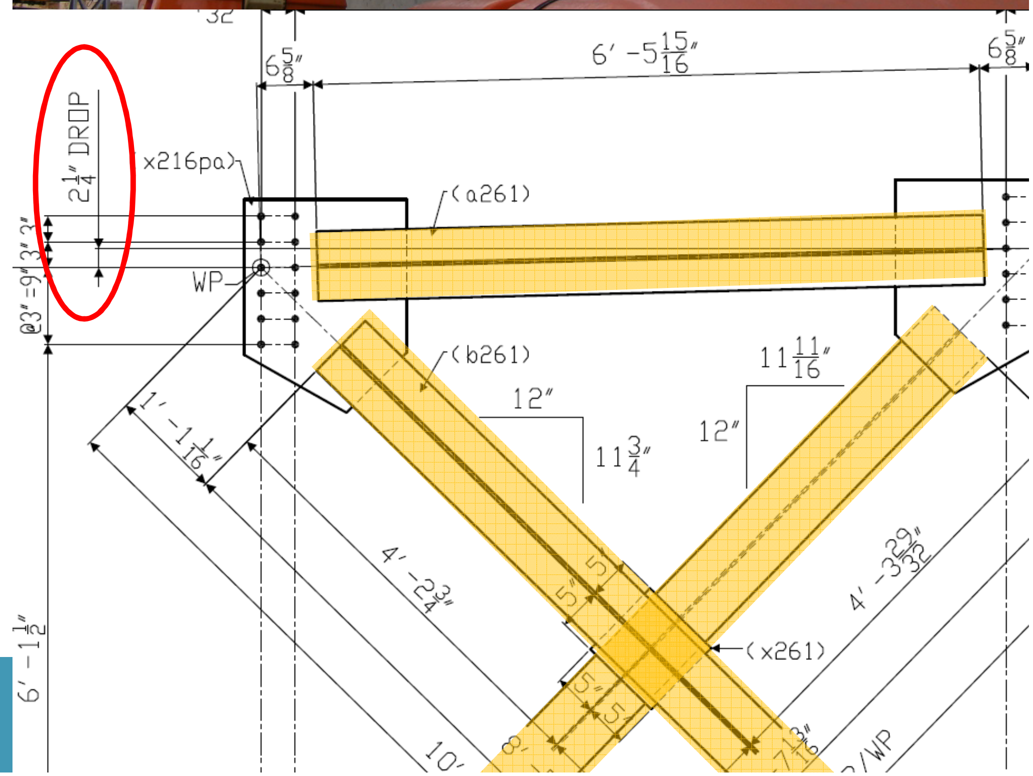
What is Fit and Why is it Important?

The "fit" or "fit condition" of an I-girder bridge refers to the deflected girder geometry associated with a specific load condition in which the cross-frames or diaphragms are detailed to connect to the girders. Consideration of the fit condition is important because the appropriate fit decision can provide a significant benefit to the constructability and the overall performance of the bridge system.

In all bridge systems (trusses, arches, etc.) the steel components change shape between the fabricated condition, the erected condition, and the final condition. Therefore the associated relationship, or fitting, of the members also changes. When the changes are small, the fit choice can be inconsequential, but when the changes are large, the proper fit choice is essential for achieving a successful project.

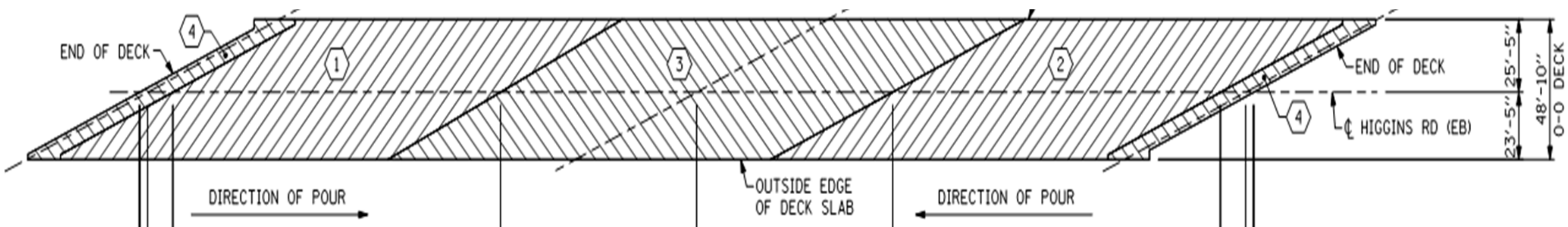
Fit Condition

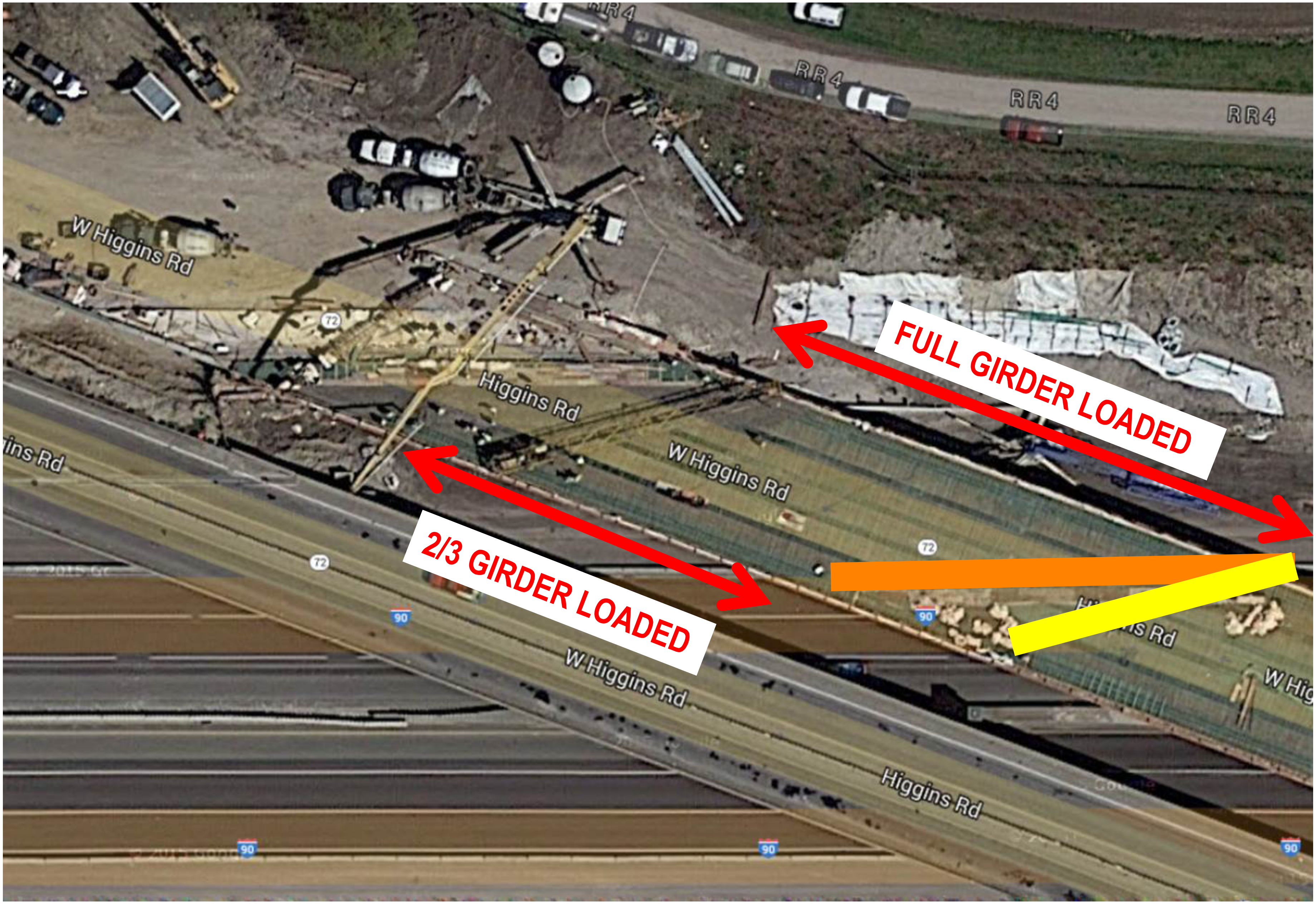
- Achieved via girder drops on the shop drawings
  - Drops are the difference in elevation between the top of webs for adjacent girders.
  - Drops are comprised of:
    - differential deflection
    - roadway profile
    - deck cross slope



Deck Placement Analysis

- Girder camber is dependent on the sequence of the deck placement
- Difference between single monolithic deck pour and accumulated deflection due to the deck placement sequence
- Verify deck stresses resulting from pour sequence will not result in cracking





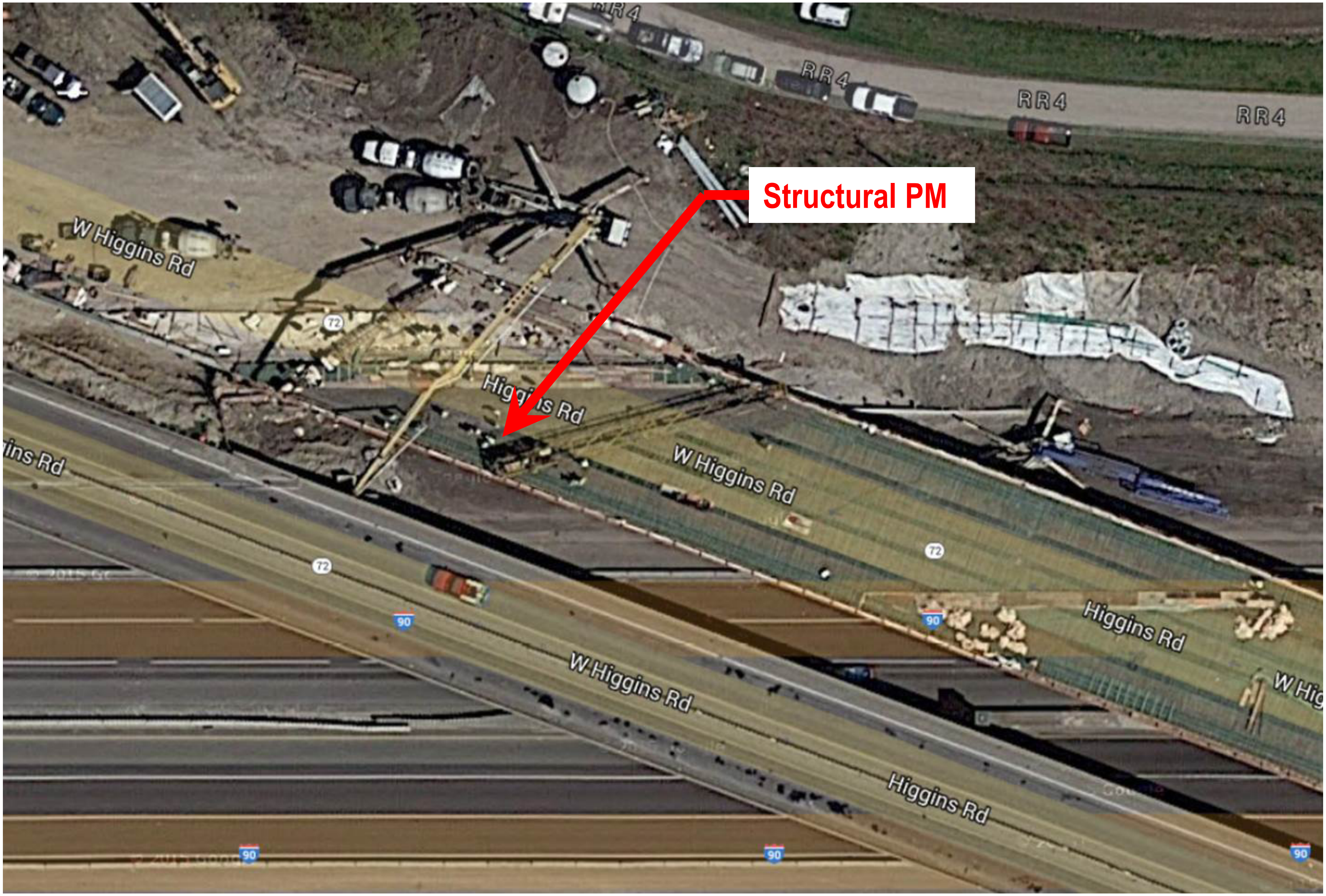
FULL GIRDER LOADED
2/3 GIRDER LOADED
W Higgins Rd
Higgins Rd
RR4

Deck Placement

- Placement of concrete along skew to load girders equally
- Place concrete along bridge skew ahead of paver skew and use retarder to delay set

Deck Placement

- Bridge Paver rails extended to approach


Structural PM
RR4
RR4
RR4
W Higgins Rd
Higgins Rd
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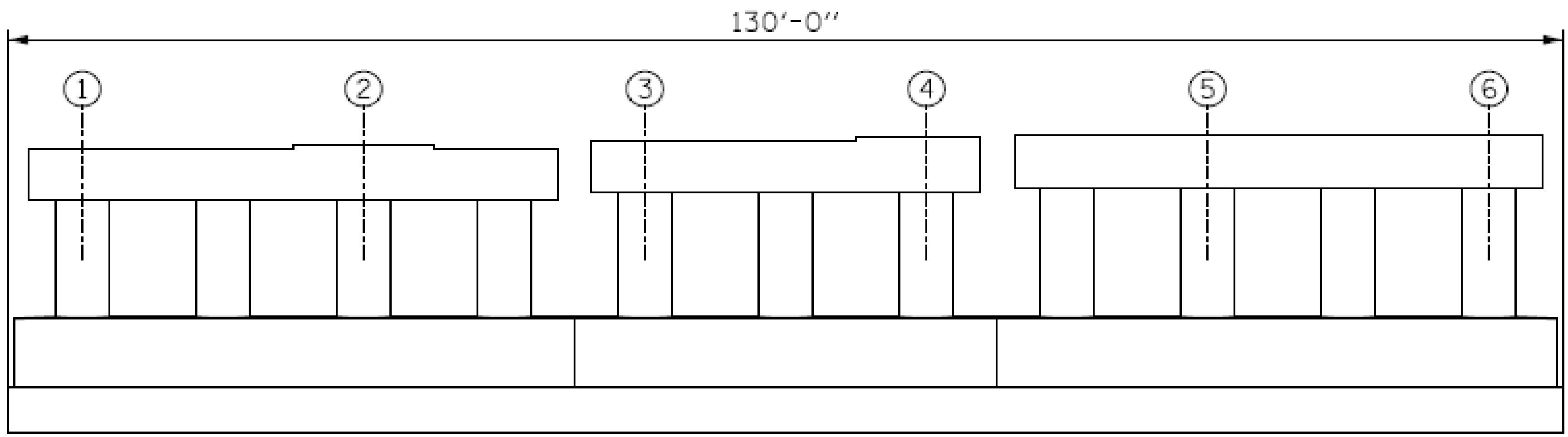
Higgins Rd
72
90

Pier Design

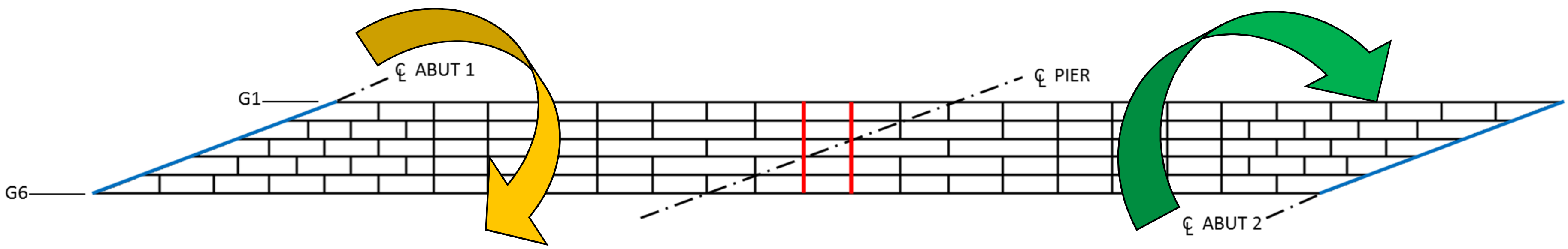
- 49’ wide bridge = 130’ long pier along skew
- 3 segments, each supporting 2 girders

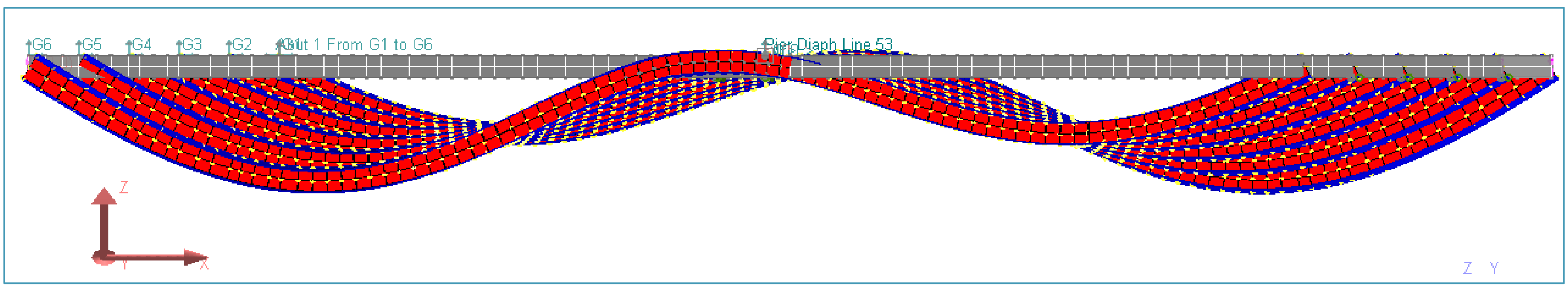


Pier Design

Pier Design: Effect of Skew

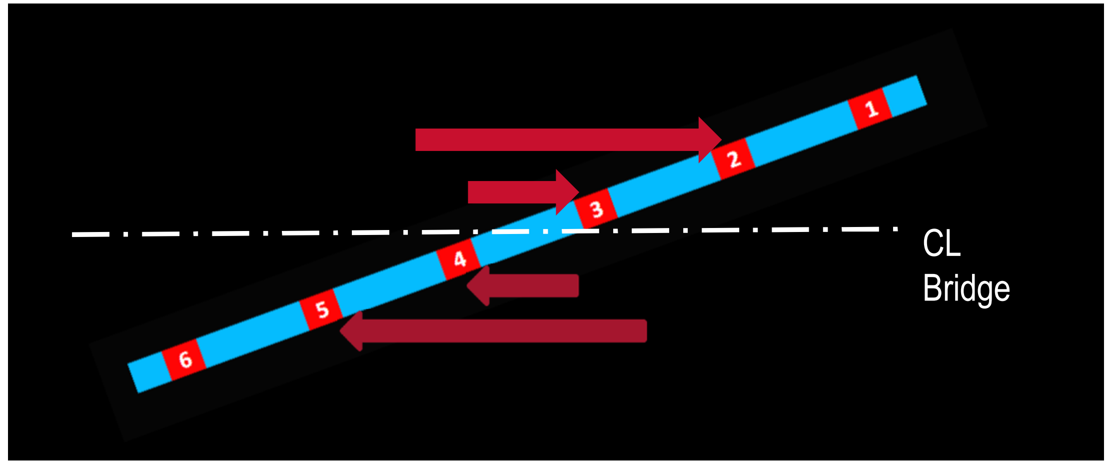
- Opposite direction of rotation between span 1 and 2

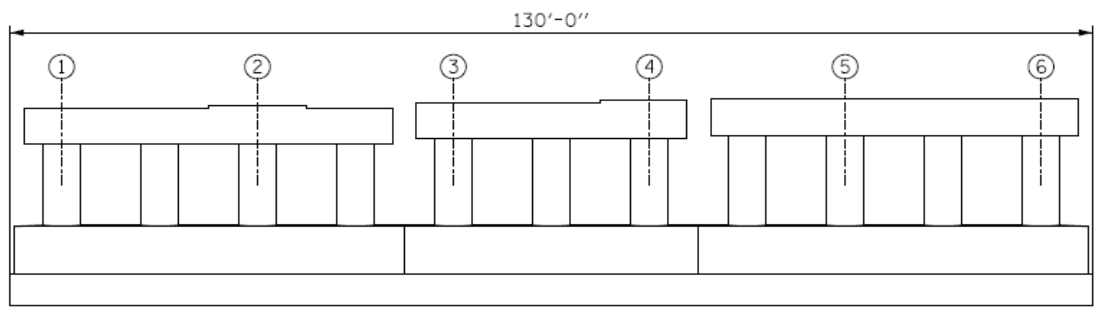




Pier Design

- Severe skew and fixed bearing condition led to high lateral forces in opposite directions
- Segmented pier:
  - o Better accommodate internal thermal force demands
  - o Reduce torsion in pier cap
- Circular columns directly under girders to effectively carry vertical reaction
- Intermediate circular columns to effectively resist fixed horizontal bearing reactions



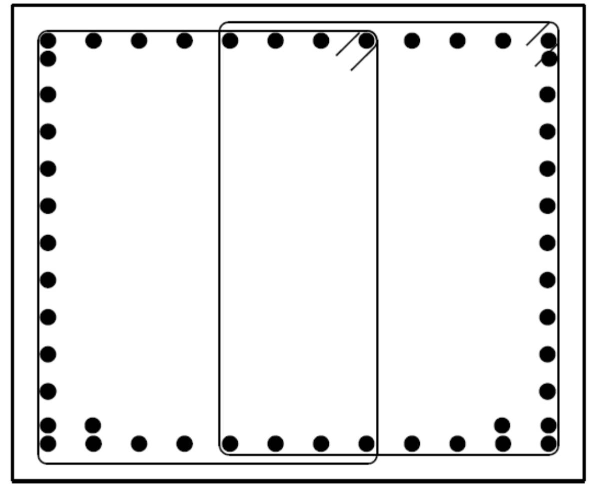


Pier Cap Design

- End Result:

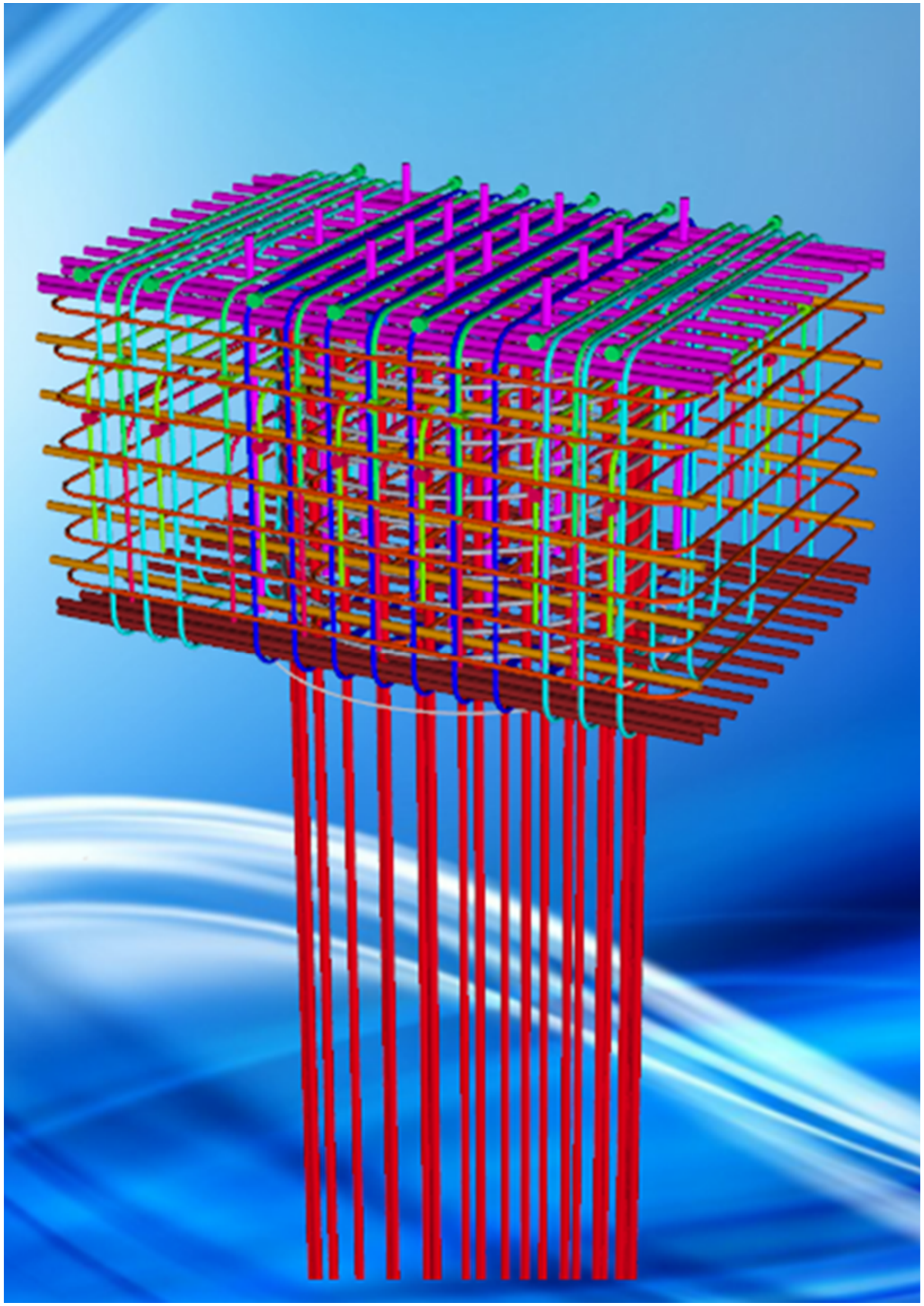
  Horizontal bearing reactions approximately equal to vertical reactions

- High torsional demand
  - No. 10 bars all around
- Special design considerations at fixed bearing locations



Concrete Anchorage Design

- Specialized approach with seismic-like detailing
  - Supplemental horizontal and vertical stirrups
  - Welded hoop bars
  - Embedded anchor bolts
  - Bar terminators
- Use of parametric tools
  - Clash detection
  - Verify sequence



Pier Cap Detailing

Bar Terminator

Anchorage Reinforcement

Pier

- Welded hoop bars to confine core for anchorage

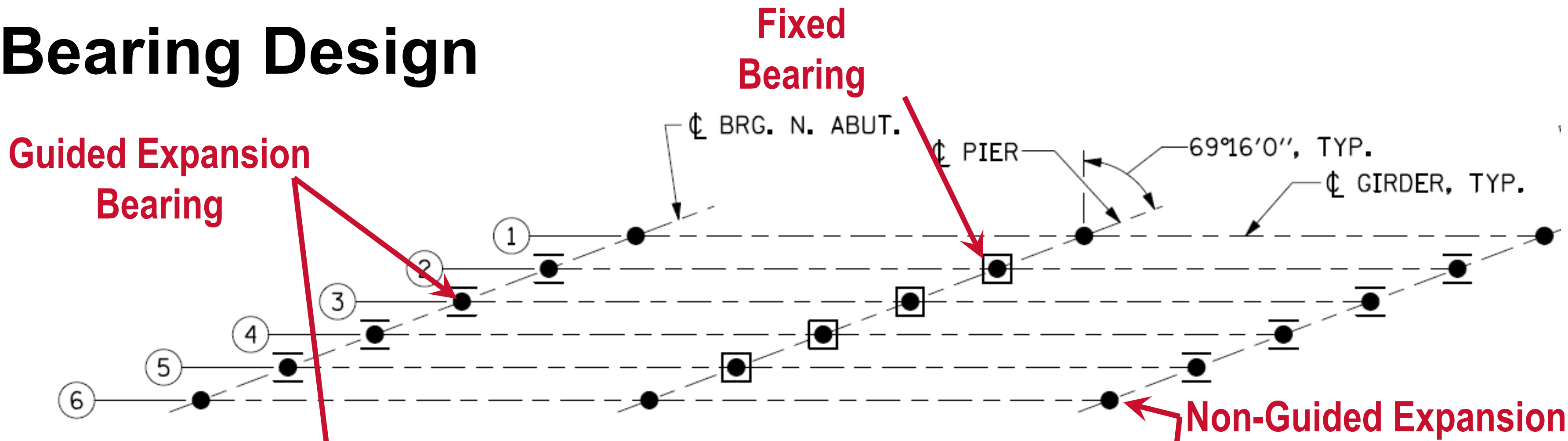
Fixed Bearing

Pier

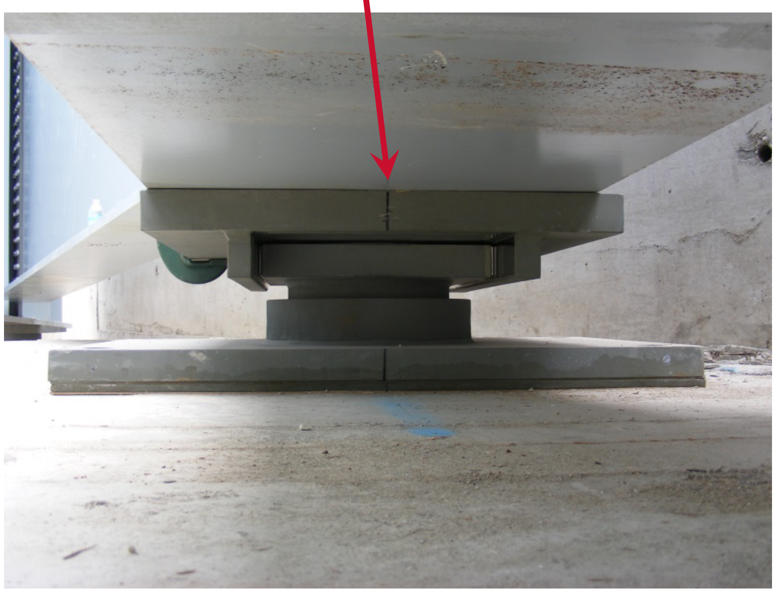
Fixed Bearing

Non Guided Expansion Bearing

Bearing Design

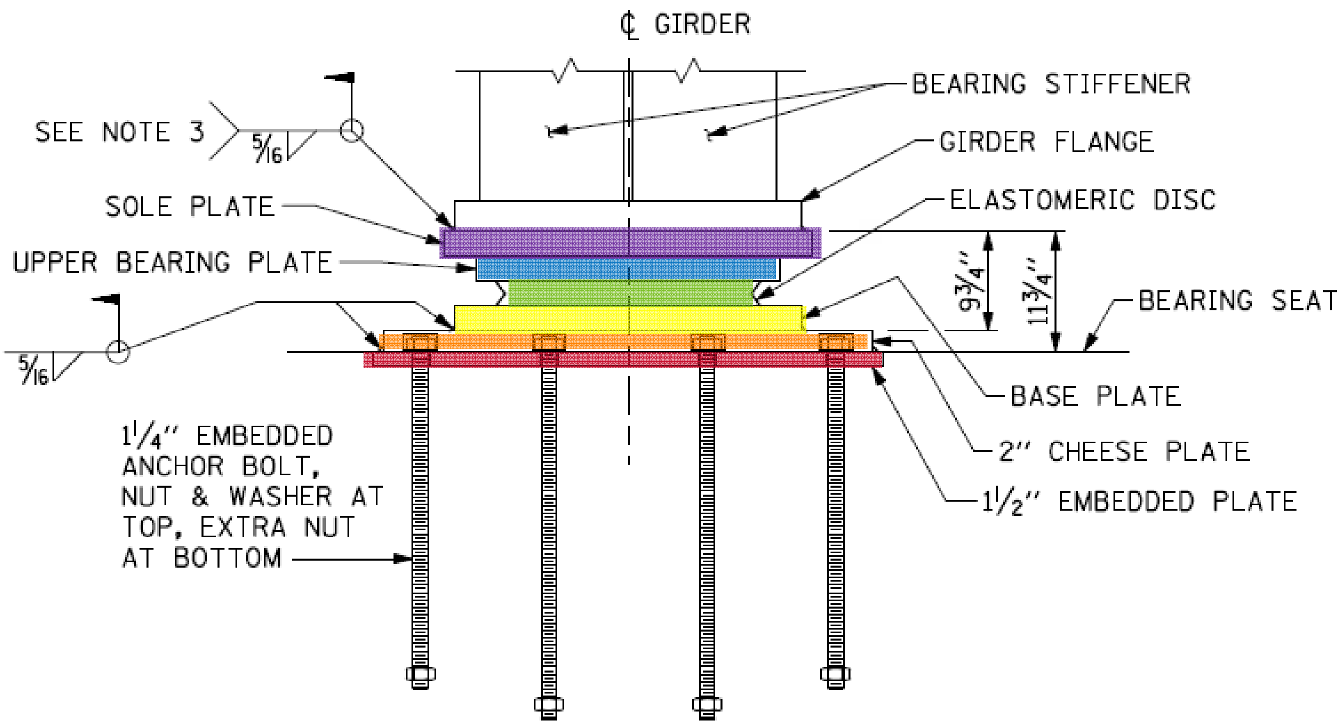


SCHEMATIC BEARING PLAN



Bearing Design

- High Load Multi-Rotational Bearings
- Disc bearings were specified (rotation at abutments > 0.05 radians)



FIXED DISC BEARING ASSEMBLY

AT PIER - GIRDERS 2, 5, 8, 11

Bearing Design

Concrete
Placement Hole

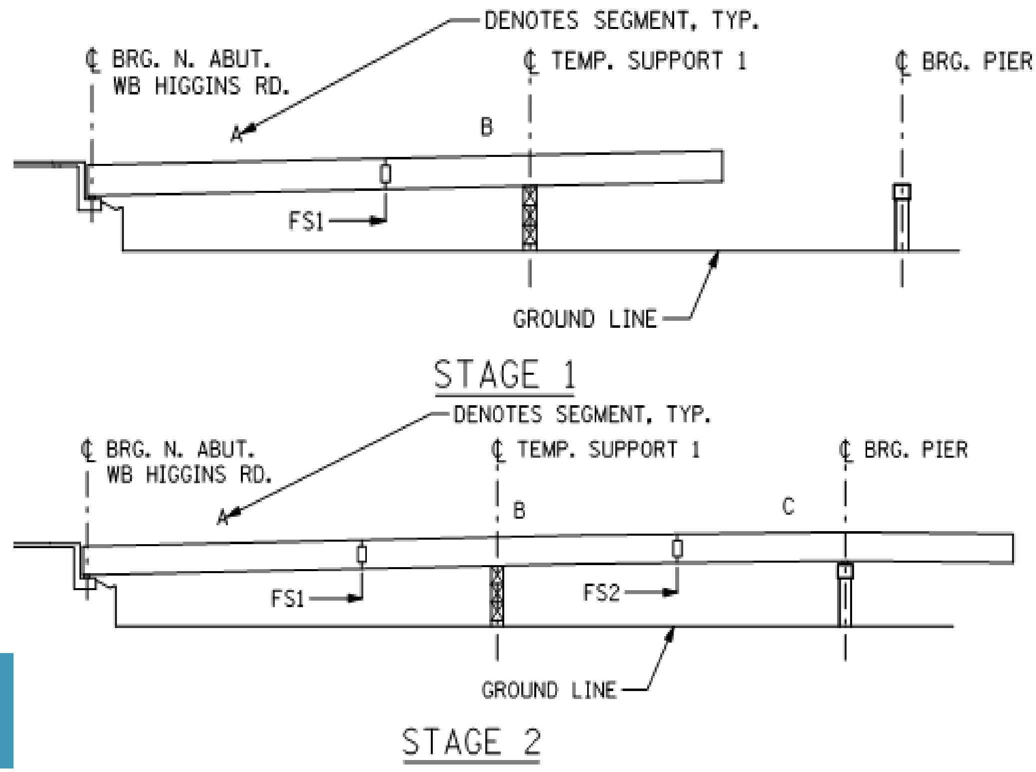
Anchor bolts
threaded through
embedded plate

Swivel Type Modular Expansion Joint

- Multi-directional movement capability
- Detail girders and end diaphragms to accommodate joint
- Special closure pour at joints
  - To minimize movement due to dead load effects (racking)
  - To reduce shrinkage effects

Conceptual Erection Sequence Analysis

- AASHTO LRFD Requirements
  - Article 2.5.3 Constructability
  - "Where the bridge is of unusual complexity, such that it would be unreasonable to expect an experienced contractor to predict and ***estimate a suitable method of construction*** while bidding the project, ***at least one feasible construction method shall be indicated in the contract documents***."



Conceptual Erection Sequence Analysis

- Use LARSA 3D FEM to check:
  - Temporary support structure placement
  - Hold cranes required
  - Girder stresses, deflections, reactions (no uplift)
- Potential issues:
  - Girder buckling capacity greatly reduced due to long unbraced lengths
  - Loading is less than in the final condition, but the girder capacity is also less

Shop Fit-Up

Extreme Skew

Presentation Outline

- Introduction
- Behavior of Skewed Structures
- Cross Frames and Diaphragms
- Framing Plan
- Analysis
- Case Study
  - Detailing and Fit
  - Deck Placement Considerations
  - Impacts to Pier Design
  - Effects on Bearing Design
  - Expansion Joints
  - Conceptual Erection Sequence
  - Shop Fit-Up
- Summary

Summary

- Try to minimize skew in the planning process
- Recognize alternative load paths at skewed supports
- Recognize when a refined 3D analysis is warranted
- Be cognizant of high lateral forces at fixed bearings of a skewed support
- Specify fit condition for the girders and cross-frames
- Consider shop assembly to verify fit-up
- Place deck concrete along skew
- Follow these steps to reduce risk of geometry control issues and construction delays and claims

QUESTIONS……

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